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Engineering Parameters for Environmental Remediation Technologies

Suresh R. Kikkeri

Woodward-Clyde Federal Services
200 Orchard Ridge Drive, Suite 101
Gaithersburg, MD 20878

Eric R. Ness

U.S. Coast Guard
Research and Development Center
1082 Shennecossett Road
Groton, CT 06340-6096
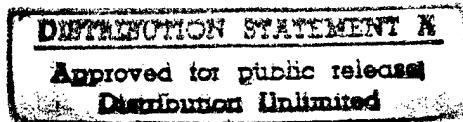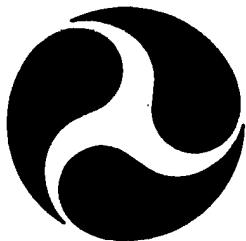
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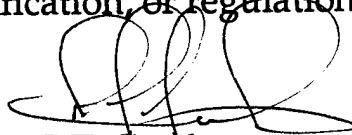
G.T. Gunther
Commanding Officer
United States Coast Guard
Research & Development Center
1082 Shennecossett Road
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16. Abstract

This document identifies engineering parameters and establishes ranges of values for 33 environmental remediation technologies. The main purpose is to provide U.S. Coast Guard (USCG) civil engineering personnel with summarized information regarding matrix characteristics and design parameters that are applicable to each of the technologies. This information is intended to guide USCG personnel when making decisions regarding the selection of appropriate remediation technologies. This document has been developed to be used as a companion document to the Remediation Technologies Screening Matrix and Reference Guide (EPA/542/B-94/013).

17. Key Words

technologies, remediation technologies, remediation design, matrix characteristics, remediation, environmental remediation, cleanup, treatment, engineering design, alternative, parameters, soil, groundwater

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METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
AREA				
in²	square inches	6.5	square centimeters	cm²
ft²	square feet	0.09	square meters	m²
yd²	square yards	0.8	square meters	m²
mi²	square miles	2.6	square kilometers	km²
	acres	0.4	hectares	ha
MASS (WEIGHT)				
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
VOLUME				
tsp	teaspoons	5	milliliters	ml
tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft³	cubic feet	0.03	cubic meters	m³
yd³	cubic yards	0.76	cubic meters	m³
TEMPERATURE (EXACT)				
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly).

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
AREA				
cm²	square centimeters	0.16	square inches	in²
m²	square meters	1.2	square yards	yd²
km²	square kilometers	0.4	square miles	mi²
ha	hectares (10,000 m²)	2.5	acres	
MASS (WEIGHT)				
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
VOLUME				
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	0.125	cups	c
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m³	cubic meters	35	cubic feet	ft³
m³	cubic meters	1.3	cubic yards	yd³
TEMPERATURE (EXACT)				
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F

°F -40 0 |32| 80 98.6 120 160 200 |212| °F
°C -40 -20 0 |20| 37 40 60 80 100 °C

TABLE OF CONTENTS

TABLE OF CONTENTS (Concluded)

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

atm	atmospheres
BOD	Biochemical Oxygen Demand
C	carbon
$CaCO_3$	calcium carbonate (limestone)
C_e	effluent concentration of contaminant
CEU	Civil Engineering Unit
cfm	cubic feet per minute
cfu	colony forming unit
C_i	influent concentration of contaminant
cm	centimeters
cms	square centimeters
CO_2	carbon dioxide
COD	Chemical Oxygen Demand
CSPBT	Controlled Solid Phase Biological Treatment
DCA	1,1-dichloroethane
ETC	Environmental Transportation Consultants
ft^2	square feet
ft^3	cubic feet
GAC	Granular Activated Carbon
gdw	gram dry weight
gpm	gallons per minute
H_2O_2	Hydrogen peroxide
HDPE	High Density Polyethylene
Hg	Mercury
HMX	Octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine- -cyclo-tetramethylene-tetranitramine
hr	hour

LIST OF ACRONYMS

HTTD	High Temperature Thermal Desorption
kg	kilogram
KOH	potassium hydroxide
kw	kilowatt
kwh	kilowatt - hour
l	liter
lbs	pounds
LEL	Lower Explosive Limit
m^3	cubic meters
meq	milliequivalents
mg	milligram
MGM	Multi-fuel Glass Melter
Mhz	megahertz
min	minute
mm	millimeter
mol	mole
mV	millivolts
N	nitrogen
NAPLs	Non Aqueous Phase Liquids
NH_3-N	ammonia nitrogen
nm	nanometers
°C	degrees celsius
°F	degrees fahrenheit
PAH	Polyaromatic Hydrocarbon
PCA	polychloroethane
PCB	Polychloronated biphenol
PCE	polychloroethene

LIST OF ACRONYMS

PCP	pentachlorophenol
pE	redox potential
pH	hydrogen ion concentration
PO_4-P	phosphate phosphorus
ppb	parts per billion
ppm	parts per million
ppmv	parts per million by volume
psi	pounds per square inch
psig	pounds per square inch gauge
RDC	Research and Development Center
RDX	Hexahydro-1,3,5-trinitro-s-triazine--Cyclo-trimethylene-trinitramine
Redox	reduction/oxidation
RF	Radio Frequency
RKI	Rotary Kiln Incineration
ROI	Radius of Influence
scfm	standard cubic feet per minute
scft	standard cubic feet
SDS	a type of surfactant
sec	second
S_{RN}	degree of saturation (fraction of pore space occupied by water, gases or NAPLs)
SVE	Soil Vapor Extraction
SVOC	Semi-Volatile Organic Compounds
TCA	trichloroethane
TCE	trichloroethene
ThOD	Theoritical Oxygen Demand

LIST OF ACRONYMS

TNT	trinitrotoluene
TPH	Total Petroleum Hydrocarbon
UCS	Unconfined Compressive Strength
USAF	United States Air Force
USCG	United States Coast Guard
USEPA	United States Environmental Protection Agency
UST	Underground Storage Tank
UV	Ultraviolet
VOC	Volatile Organic Compound
W	watt
yd^3	cubic yards

This document, *Engineering Parameters for Environmental Remediation Technologies,* was developed by the United States Coast Guard (USCG) Research and Development Center (RDC) in conjunction with the John A. Volpe National Transportation Systems Center (Volpe Center) and their consultant, Environmental Transportation Consultants (ETC). It provides recommended ranges of values for selected engineering parameters of 33 engineering technologies likely to be used by the USCG. Descriptions of technologies can be found in the EPA publication *Remediation Technologies Screening Matrix and Reference Guide* (EPA/542/B-94/013).The document presented here, *Engineering Parameters for Environmental Remediation Technologies,* is intended to be used as a companion document to the *Remediation Technologies Screening Matrix and Reference Guide.*

1.1   PURPOSE

The *Remediation Technologies Screening Matrix and Reference Guide*, prepared by the Federal Remediation Technologies Roundtable and published by the United States Environmental Protection Agency (USEPA), was intended to be used to screen and evaluate candidate cleanup technologies for contaminated sites in order to assist remedial project managers in selecting a remedial alternative. While the USEPA document gives a detailed description of remedial technologies being practiced at various federal installations, it does not provide specific ranges of values of the engineering parameters that are important to implement a particular technology for a specific site. This document, *Engineering Parameters for Environmental Remediation Technologies*, identifies engineering parameters and establishes ranges of values for selected technologies.

The main purpose of this document is to provide USCG Civil Engineering personnel with summarized information regarding matrix characteristics and engineering design parameters that are applicable to each of the technologies. This information is intended to guide USCG personnel when making decisions regarding the selection of appropriate remediation technologies. A companion document, *Remediation of Contaminated Media at USCG Facilities,* includes a collection of parameters and cost data pertaining to remediation efforts at USCG facilities.

1.2   ORGANIZATION

This document has five sections. Section 1.0 is an introduction. Section 2.0 explains the methods used to gather the data on various remediation technologies. Section 3.0 lists the remediation technologies considered in this document. Section 4.0 summarizes the established ranges of values for the engineering parameters. Section 5.0 lists the references used to prepare this document. Appendix A includes all figures referenced in this document. Appendix B includes all tables referenced in this document.

Data pertaining to the remediation technologies were collected through a literature survey, and the projects at USCG facilities. The USCG projects considered included completed projects, current projects, and projects that have finalized designs.

Literature Survey: An in-depth literature survey was conducted to identify the suitable matrix characteristics and the important engineering design parameters for each of the technologies. Literature cited included USEPA publications, text books, study materials prepared by Universities, Conference proceedings, and other published papers in journals and magazines.

USCG Projects: The review of USCG projects identified technologies primarily associated with the remediation of hydrocarbon-contaminated media. Details pertaining to the various technologies used at USCG facilities were collected and the engineering parameters used in these projects were identified. These parameters were also used to establish ranges of values for engineering parameters.

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Technologies considered in this document are presented in Table 3-1. Numbers in the first column are those used in the *Remediation Technologies Screening Matrix and Reference Guide (EPA/542/B-94/013)* to identify specific remediation technologies. The second column provides the names of the remediation technologies and the third lists the applicable matrix type in which it is typically used.

TABLE 3-1: REMEDIATION TECHNOLOGIES

Reference Number	Type of Technology	Matrix
4.1	Biodegradation - In Situ	Soil
4.2	Bioventing	Soil
4.6	Soil Vapor Extraction - In Situ	Soil
4.7	Solidification/Stabilization - In Situ	Soil
4.8	Thermally Enhanced Soil Vapor Extraction	Soil
4.10	Composting	Soil
4.11	Controlled Solid Phase Biological Treatment	Soil
4.12	Landfarming	Soil
4.13	Slurry Phase Biological Treatment	Soil
4.14	Chemical Reduction/Oxidation	Soil
4.17	Soil Washing - Ex Situ	Soil
4.18	Soil Vapor Extraction - Ex Situ	Soil
4.19	Solidification/Stabilization - Ex Situ	Soil
4.20	Solvent Extraction	Soil
4.21	High Temperature Thermal Desorption	Soil
4.23	Incineration	Soil
4.24	Low Temperature Thermal Desorption	Soil
4.27	Vitrification	Soil
4.29	Natural Attenuation (Intrinsic Remediation)	Soil
4.32	Oxygen Enhancement with Air Sparging	Water
4.33	Oxygen Enhancement with Hydrogen Peroxide	Water
4.34	Air Sparging	Water
4.36	Dual Phase Extraction	Water
4.37	Free Product Recovery	Water
4.41	Slurry Walls	Water
4.43	Bioreactors	Water
4.44	Air Stripping	Water
4.47	Liquid Phase Carbon Adsorption	Water
4.49	Ultraviolet (UV) Oxidation	Water
4.50	Natural Attenuation (Intrinsic Remediation)	Water
4.51	Biofiltration	Air
4.54	Oxidation	Air
4.55	Vapor-Phase Carbon Adsorption	Air

Through a thorough literature survey, engineering parameters applicable to each of the technologies identified in Section 3.0 of this document are listed in sections 4-1 through 4-55. These parameters can be grouped as matrix characteristics, operating parameters, or biological parameters. Based on the literature survey and the projects at USCG facilities, ranges of values were established.

The quantity of information listed for each of the technologies was limited to the information available at the time of this document's publication. Therefore, extensively used technologies had more information available than less often used technologies. For some of these less commonly used technologies, minimal information was available to establish ranges of values. In these situations, only the available information is presented under each of these technologies.

The section numbers (4.1 through 4.55) exactly match with the section numbers used in the USEPA publication *Remediation Technologies Screening Matrix and Reference Guide (EPA/542/B-94/013)*. For example, Section 4.2 in the *Remediation Technologies Screening Matrix and Reference Guide* provides the description, applicability, limitations, data needs, performance, and cost information for bioventing. Section 4.2 in this document provides the ranges of engineering parameters for bioventing.

4.1 BIODEGRADATION

Engineering Parameters	Range of Values	References
Matrix Characteristics		
Type of Contaminants	Organics (see Table 1 in appendix B)	USEPA 1991a
Soil Classification[1]	Soil with less clay (sandy soil)	
Moisture Content	25 % - 85%	University of Wisconsin 1995; Park and Sims 1994
Redox Potential[2]	pE + of 17.5 to 2.7	USEPA 1990a; USEPA 1994a; and Sawyer and McCarty 1985
Hydraulic Conductivity of the Soil	$>10^{-4}$ cm/sec	Testa 1995
pH[2,3]	5- 9	McCoy and Associates 1992; USEPA 1995a
Soil Temperature[4]	$4° C- 40°C$ (Optimum is $25°C$)	O'Brien and Gere 1995; Norris and Eckenfelder 1994
Microbial Population Density	10^3 to 10^7 colony-forming units per gram	Leavitt 1992; Cleary 1995
Presence of Co-metabolite[5]	Varies	USEPA 1990a
Cation Exchange Capacity	Around 0.5 mhos/cm	
Operating Parameters		
Type of Biodegradation	Generally Aerobic	
Oxygen Utilization Rates	0.02 to 0.99 percent oxygen/hour	Hinchee and Ong 1992
Rate of Biodegradation	0.4 to 19 mg/kg	Hinchee and Ong 1992
Minimum Oxygen Content for biodegradation	5 %	O'Brien & Gere 1995
Microbial Activity - Oxygen Uptake Rate[6]	Hydrocarbon : Oxygen = 1:3.0 to 1:3.5	Makdisi et al. 1993; and Norris and Eckenfelder 1994
Microbial Activity - Carbon Dioxide Evaluation	0.05 - 9.1%	Based on USCG Project at Air Station Sitka, AK CEU Juneau
Nutrients - Carbon:Nitrogen:Phosphorus[7]	100:10:1 - 500:10:1	USEPA 1990a; and Miller et al. 1992; O'Brien & Gere 1995
Need for a Treatability or Feasibility Test	Usually needed	
Rate of Warm Water Application	1 gallon/min at 35°C	Sayles et al. 1992

FOOTNOTES - 4.1 BIODEGRADATION

1. Relationships between soil types, particle sizes, and hydraulic conductivity are presented in Figure 1 (Appendix A).

2. The pH (hydrogen ion activity) and pE (redox potential) of the geologic materials and the waste stream strongly influence contaminant mobility. The pH affects the speciation of many dissolved chemical constituents, which in turn determines solubility and reactivity. Ion exchange and hydrolysis reactions are also particularly sensitive to pH. pE influences many precipitation and dissolution reactions, particularly those involving iron and manganese, and determines in large measure the type of biodegradation that occurs.

   Redox potential is generally expressed in volts, E, or as the negative logarithm of the electron activity, pE. At neutral pH, aerobic conditions are associated with a pE of about 13, and anaerobic by pE below -3. For each unit decrease in pH, the respective values for pE increase about one unit.

3. Near-neutral pH values are most conductive to biodegradation. The pH can be increased using lime products, such as limestone, or it can be lowered with acidic materials.

4. Bioremediation can occur over the 15 - 45° C temperature range, but is most effective over the 20° C - 40° C (Autry and Ellis 1993). Metabolic rate of the microorganisms reaches its maximum near 25° C (O'Brien & Gere 1995). According to Norris and Eckenfelder (1994), most aerobic biological-treatment processes operate within a temperature range of 4 to 39 ° C and they also mention that in cold climate areas the indigenous microorganisms are likely to be more active at the lower end of the acceptable temperature range than are bacteria indigenous to more temperate climates. Cold temperatures and the depth of contamination inhibit biological degradation. If the depth of the soil that undergoes bioremediation is deep, anaerobic conditions set in (Adriaens *et al.* 1995).

5. Co-metabolism is defined as the biodegradation of an organic substance by a microbe that cannot use the compound for growth and hence must rely on other compounds for carbon and energy.

6. In order to biodegrade one pound of fuel hydrocarbons to carbon dioxide and water, approximately 3.5 pounds of oxygen are required.

FOOTNOTES - 4.1 BIODEGRADATION (continued)

7.   According to Norris and Eckenfelder (1994), a general rule of thumb for nutrient requirements ranges from 3 to 10 pounds of nitrogen and from 0.3 to 1 pound of phosphorous per 100 pounds of biodegradable organic carbon. Trace nutrient requirements for biological oxidation are presented in Table 2 (Appendix B).

In Air Station Sitka, AK (CEU Juneau), hand broadcast fertilizer (21%N, 3%P and 5% potash) was used. Rate of application was 10 to 15 pounds per 1000 square feet - every three months.

4.2 BIOVENTING

Engineering Parameters	Range of Values	References
Matrix Characteristics		
Contaminate Type	Organic	
Soil Classification[1]	Soil with less clay (sandy soil)	
Moisture Content[2]	25 - 85 % field capacity	University of Wisconsin 1995; Park and Sims 1994
Air permeability	$> 10^{-5}$ cm/sec (1 darcy)	University of Wisconsin 1995
Permeability of the Soil	$> 10^{-5}$ cm/sec (> 1 darcy)	USEPA 1993a; University of Wisconsin 1995
Hydraulic Conductivity[1]	4 to 1000 ft/day	USEPA 1995a
pH	5 - 9	McCoy and Associates 1992; USEPA 1995a
Temperature	5°C - 40°C (Optimum is 25°C)	University of Wisconsin 1995; Autry and Ellis 1993; and O'Brien and Gere 1995
Depth to Water Table	> 5 feet	University of Wisconsin 1995
Nonaqueous Phase Liquids	< 10,000 mg/kg of subsurface soils	University of Wisconsin 1995
NAPLs, Residual Saturation[3], S_{RN}	0.002 to 0.60 (typical 0.10 to 0.20)	Cleary 1995
Henry's Constant[4]	> 0.001	University of Wisconsin 1995
Optimum Native Microbe Count (plate count)	$10^3 - 10^7$ cfu/gdw	Cleary 1995; Leavitt 1992
Operating Parameters		
Air Flow Rate	2.5 - 10 cubic feet/minute/well	University of Wisconsin 1995
Air Injection Point	2 to 6 feet below grade	Sayles *et al.* 1992
Spacing of the Wells	30 feet apart	Sayles *et al.* 1992
Air Exchange Rage	0.25 to 1 pore volume (0.6 typical)	USAF 1992; USEPA 1995a
Rate of warm water application[5]	1 gallon/min at 35° C	Sayles *et al.* 1992
Type of Biodegradation	Aerobic	
Min. oxygen content for biodegradation	5 %	O'Brien and Gere 1995

4.2 BIOVENTING (continued)

Engineering Parameters	Range of Values	References
Microbial Activity - Oxygen Uptake Rate[6]	Hydrocarbon : Oxygen = 1 : 3.0 to 1:3.5	Makdisi *et al.* 1993; and Norris and Eckenfelder 1994
Microbial Activity - Carbon Dioxide Evaluation	0.05 - 9.1%	Based on USCG project at Air Station Sitka, AK CEU Juneau
Air needed for Biodegradation	13 pounds of air/pound of hydrocarbons	USAF 1992
Microbial Activity - Hydrocarbon Degradation	170 - 5210 mg TPH/kg soil/year	Based on the operation at Kodiak, AK (USCG facility)
Nutrients - Carbon:Nitrogen:Phosphorus[7]	100:10:1 - 500:10:1	O'Brien and Gere 1995 USEPA 1990a; and Miller et al. 1992
Degradation of Volatile Petroleum Hydrocarbons	99%	USEPA 1995a

FOOTNOTES - 4.2 BIOVENTING

1. Relationships between soil types, particle sizes, and hydraulic conductivity are presented in Figure 1 (Appendix A).

2. Bioventing technologies implemented at two USCG facilities - Traverse City, MI and Air Station San Diego, CA had different moisture contents; the former location had a moisture content of 3.5% and at the latter place, it ranged from 2.5 to 50.1%.

3. Degree of saturation is the fraction of total void or pore space occupied by water, gases or NAPLs. Residual saturation is defined as the saturation at which the water, gases or NAPLs become discontinuous and are immobilized.

4. Henry's Constant is defined as the ratio of compound's concentration in air to that concentration in water (O'Brien & Gere 1995). Henry's constants for selected constituents are presented in Table 3 (Appendix B). Details of Henry's constants for various contaminants are also presented in Figure 2 (Appendix A).

5. The site under consideration can be heated by applying warm water from soaker hoses 2 feet below the surface. Soaker hoses can be placed 10 feet apart.

6. In order to biodegrade one pound of fuel hydrocarbon to carbon dioxide and water, approximately 3.5 pounds of oxygen are required.

7. The system can be supplemented with inorganic nitrogen and phosphorus compounds, such as ammonium nitrate, ammonium phosphates, and ammonium dihydrogen phosphate.

4.6   SOIL VAPOR EXTRACTION - In Situ

Engineering Parameters	Range of Values	References
Matrix Characteristics		
Types of Contaminants	Chlorinated Solvents, Petroleum hydrocarbons, SVOCs, VOCs, Pesticides	
Soil Classification[1]	Sandy thru silty/clay soil	USEPA 1991b
Air Permeability	$> 10^{-10}$ cm^2 (0.01 darcies)	
Porosity	0.25 (effective) typically assumed	Based on Base Miami Beach, design CEU Miami
Hydraulic Conductivity[1]	$>10^{-10}$ cm/sec.	USEPA 1995b
Moisture Content	<50%	
Depth to Water Table	>5 feet	
Henry's Constant of the Volatile Compounds[2]	> 0.001	O'Brien and Gere 1995
Operating Parameters		
Air Flow Rate[3]	35 up to 4500 cfm or 136 sfm/well	Based on USCG Projects; USEPA 1995b
Half Lives for an Airflow of 3000 scfm[4]	PCA = 296 days PCE = 47 days TCE =50 days	USEPA 1995b
Operating Pressure/Vacuum	Up to 20" Hg	USEPA 1995b
Typical Diameter of the Extraction Well[5]	2 to 4 inches	
Typical Depth of Extraction Wells	Typical is 15 to 100 feet.	USEPA 1994b
Placement of the Screen[6]	Near the water table	
Treatment Required for Air emissions	Activated Carbon typically Biofilters are coming into use.	
Effectiveness	Not effective in the saturated zone	
Design Life of the SVE System	30 years	USEPA 1995b

FOOTNOTES - 4.6 SOIL VAPOR EXTRACTION

1. Clayey or silty soils may be effectively ventilated by the usual levels of vacuum developed in an SVE system (USEPA 1991b). Relationships between soil types, particle sizes, and hydraulic conductivity are presented in Figure 1 (Appendix A).

   SVE systems designed at this low hydraulic conductivity value (10^{-10} cm/sec) are high vacuum systems measuring vacuum in inches of mercury (Hg) typically using liquid ring pumps.

2. Henry's Constant is defined as the ratio of compound's concentration in air to that concentration in water (O'Brien & Gere 1995). According to USEPA (1991b and 1994b), this technology works well for volatile compounds with Henry's constant greater than 0.01 or a vapor pressure greater than 0.02 inches of mercury.

3. At Air Station Elizabeth City (CEU Cleveland), passive wind turbines were used. The flow rate varied from 4 to 61 cfm/wind turbine. USEPA (1995b) has reported the design airflow of up to 4500 scfm with 20 inches of mercury.

4. The half life for a given contaminant is the time required for half of the original amount to be removed from the unsaturated zone. For a given contaminant, the initial solvent removal rate is directly proportional to the air flow rate.

5. Both the inlet and injection wells are similar in design to the extraction wells, but they are smaller in diameter (O'Brien & Gere 1995)

6. The recovery rate of VOCs is higher if a section of the screen is placed near the water table rather than the entire depth of the well. Ensure that the screen height can accommodate the highest fluctuation of the watertable in order to have screen within the unsaturated zone under all conditions.

4.7   SOLIDIFICATION/STABILIZATION (S/S) - In Situ

Engineering Parameters	Range of Values	References
Matrix Characteristics		
Types of Contaminants[1]	Metals, PCBs, Oil sludges, Pesticides and organics (resins, etc.), Creosote wastes	USEPA 1990a
Commonly Used S/S Systems[1]	Pozzolan-portland cement systems; Lime-fly ash pozzolan systems; Sorption; and Organic binding	USEPA 1990a
Concentration of Contaminants[1]	Varies for Contaminants	USEPA 1990a
Hydraulic Conductivity (based on literature)	greater than 1×10^{-8} cm/sec	
Operating Parameters		
Percentage Binder Added[2]	5 to 35%	USEPA 1990a
Volume Increase	4 - 75%	USEPA 1990a USEPA 1992a USEPA 1992b
Increase in Density	0.6 to 11% (average is 5.5%)	USEPA 1992a
Soil Processing Capacity	40 to 80 tons per hour for shallow mixing; 20 to 50 tons per hour for deep mixing	USEPA 1992a
Minimum Unconfined Compressive Strength of the Soil after Treatment	50 pounds per square inch (according to USEPA guideline). A range of 75-866 psi has been in literature (average 410 psi)	McCoy and Associates 1992
Disposal Method	Generally on site. May also be in a landfill.	
Efficiency in Reducing the Mobility of Contaminated Waste	Greater than 95%	USEPA 1992a

FOOTNOTES - 4.7 SOLIDIFICATION/STABILIZATION (S/S) - In Situ

1. USEPA (1989a) reported the successful use of the HAZCON process in solidifying contaminated material high in organics (as high as 25%) that includes petroleum refinery waste stream. The HAZCON process is a cement-based process whose design concept is to solidify and immobilize waste contaminants. The principal difference between this process and other cement-based processes is the use of a proprietary component-Chloranan - which is claimed to permit solidification of waste materials with high organic concentrations. Immobilization of heavy metals (such as lead and zinc up to 2.3% by weight) in waste streams were successfully achieved.

    USEPA (1992a) reported the successful use of this technology for soil contaminated with pentachlorophenol (PCP) and arsenic.

2. Several case studies by USEPA (1990a) reported the amount of binder added ranging from 5% to 35% while immobilizing copper (2000 ppm), chromium (220 ppm), nickel (750 ppm), lead (2 to 100 ppm), aluminum (9500 ppm), PCBs (< 500 ppm), vinyl chloride, oil sludges, pesticides and creosote wastes. In one of the other case studies reported by USEPA (1989b), as much as 50% of binder addition has been reported (this may an exception to the range of 5% to 35%).

    In another case study where lead in the soil (80 to 120 mg/l), with an organic content of 17% was immobilized, several binder to soil ratios were successfully used (USEPA 1993b). See Table 4 in Appendix B for those ratios.

4.8 THERMALLY ENHANCED SOIL VAPOR EXTRACTION

Engineering Parameters	Range of Values	References
Matrix Characteristics		
Types of Contaminants	SVOCs, VOCs, Chlorinated Solvents, Pesticides and Fuels	
Soil Classification[1]	Sandy thru silty/clay soil	USEPA 1991b
Air Permeability	$> 10^{-10}$ cm^2 (0.01 darcies)	
Hydraulic Conductivity[2]	$>10^{-10}$ cm/sec	USEPA 1995b
Porosity	0.25 (effective) typically assumed	Based on Base Miami Beach design, CEU Miami
Henry's Constant of the Volatile Compounds[3]	> 0.001	O'Brien & Gere 1995
Minimum Concentrations of Contaminants	10 ppm	Chan et al.. 1994
Maximum Desirable Concentrations of Contaminants	Gasoline $\rightarrow$ 1,000 ppm Diesel $\rightarrow$ 10,000 ppm TCE $\rightarrow$ 200 ppm	Chan et al. 1994
Depth to Water Table	>5 feet	
Boiling Point of the Contaminant	$< 100°$ C	Chan et al. 1994
Specific Gravity of the Contaminant	< 1.0	Chan et al. 1994
Vapor Pressure of the Contaminant	< 0.12 psi	Chan et al. 1994
Viscosity of the Contaminant	< 2.0 centipoise	Chan et al. 1994
Solubility of the Contaminant in Water	< 200 mg/l	Chan et al. 1994
Operating Parameters if Hot Air and/or Steam are Used in the System		
Air Flow Rate (if hot air is used), Temperature & Pressure	700 scfm, 125° C - 135 °C & 250 psi	La Mori 1994; USEPA 1991c
Steam Flow Rate, Temperature & Pressure	3000 lbs/hr, 200° C and 400 psi	La Mori 1994; USEPA 1991c
Placement of the Screen[4]	Near the water table	
Minimum Treatment Area Needed	20,000 square feet	USEPA 1991c
Preparation of Ground	Must be flat and gradable to less than 1% slope	USEPA 1991c
Minimum Water Supply Needed	8 to 10 gpm at 30 psig	USEPA 1991c
Period of Operation	9 months for a 20,000-ton site	USEPA 1994b
Removal Efficiency	More than 90%	USEPA 1991b

4.8 THERMALLY ENHANCED SOIL VAPOR EXTRACTION (continued)

Engineering Parameters	Range of Values	References
Operating Parameters if Radio Frequency (RF) Heating is Used in the System[5]		
Power Normally Supplied by Utility Lines or Generator	208 or 240 volt AC utility lines or a diesel-fueled generator	Price *et al.* 1994
Design Temperature	150° C	USEPA 1995c
Heating System Information[6]	Operates on authorized frequencies located between 6 and 60 Mhz with radiated power levels of up to 25,000 watts per applicator	Price *et al.* 1994
Diameter of the Borehole	4 to 10 inches spaced from 10 to 50 feet apart	USEPA 1994b
Nominal Diameter of the Exciter Electrode	2.5 to 4.0 inches	Price *et al.* 1994

FOOTNOTES - 4.8 THERMALLY ENHANCED SOIL VAPOR EXTRACTION

1. Relationships between soil types, particle sizes, and hydraulic conductivity are presented in Figure 1 (Appendix A).

2. SVE systems designed at this low hydraulic conductivity value (10^{-10} cm/sec) are high vacuum systems measuring vacuums in inches of mercury (Hg) typically using liquid ring pumps.

3. Henry's Constant is defined as the ratio of compound's concentration in air to that concentration in water (O'Brien & Gere 1995). According to USEPA (1991b and 1994b), this technology works well for volatile compounds with Henry's constant greater than 0.01 or a vapor pressure greater than 0.02 inches of mercury. (See Table 3 in Appendix B)

4. The recovery rate of VOCs is higher if a section of the screen is placed near the water table rather than the entire depth of the well. Ensure that the screen height can accommodate the highest fluctuation of the watertable in order to have screen within the unsaturated zone under all conditions.

5. Other potential candidates for in-situ RF heating include hazardous wastes and sludges containing coal tar or fuel oil (Price *et al.* 1994).

6   Based on a study, it is estimated that a four applicator system using 100 kW at 13.56 Mhz could heat a volume of 150 cubic yards of sand, with 25% water by volume, to temperatures in excess of 100° C after three weeks of operation. The following lists the energy and time required to heat one cubic yard of representative materials using a 25 kw system at 100% efficiency (Price *et al.* 1994):

Sand	25 kwh (from 20° C to 100° C)	1 hour
Water	100 kwh (from 20° C to 100° C)	4 hours
Water	750 kwh (to vaporize at 100° C)	30 hours
Heavy Oil	44 kwh (from 20° C to 100° C)	1.75 hours

In another case study a 40-kw RF generator served as the energy source for the system; the target and the design temperatures were 100° C and 150° C respectively (USEPA 1995c). The case reported by USEPA (1995d), a 25-kw, 27.12 Mhz RF generator served as the energy source for the system.

4.10   COMPOSTING

Engineering Parameters	Range of Values	References
Matrix Characteristics		
Type of Contaminant	Organics	
Recommended Particle Size	For solid waste, 1" to 3"	Cookson 1995
Presence of Heavy Metal	Not desirable	
Operating Parameters		
Area Needed	Large - Dependent on Soil Quantity to be Processed	
Windrow Process: pile height pile width	4 - 5 feet 10 - 12 feet	Cookson 1995
Static Pile Process: pile height pile width	10 - 20 feet 30 - 100 feet	Cookson 1995
pH[1]	5 - 9	USEPA 1995a
Moisture Content	30-60% (Optimum is 55%)	Findlay *et al.* 1994; USEPA 1995a
Seeding and Mixing	1 to 5% (by weight) of partially decomposed solid waste or sewage sludge; or soil: compost = 2 to 8:1	Cookson, 1995; Tchobanoglous *et al.* 1977; Findlay *et al.* 1994
Mixing Rate/Frequency	3 to 7 times/week to once a week	USEPA 1995a; Minier 1993
Composting Period	1 to 6 months	USEPA 1995a
Temperature[2]	15 - 70° C	USEPA 1995a; Toomajian *et al.* 1993
Bulking Agents	Wood Chips or Animal/Vegetable Waste (for sludge composting; sludge to chips ratio = 3:2)	Cookson 1995

4.10   COMPOSTING (continued)

Engineering Parameters	Range of Values	References
Biological Activities		
Composition of the Contaminated Soil to be Composted[3]	Soil = 30% Cow manure = 21% Alfalfa = 18% Saw Dust = 18% Potatoes = 10% Hen Manure = 3%	USEPA 1995a
Nutrients (Nitrogen:Phosphorus)	6:1	
Carbon to Nitrogen Ratio[4] - before composting	35 to 50	Tchobanoglous *et al.* 1977
Carbon to Nitrogen Ratio - after composting	7 to 20	Toomajian *et al.* 1993; Tchobanoglous *et al.* 1977

FOOTNOTES - 4.10 COMPOSTING

1.   Potassium hydroxide can be added to increase the pH of the soil to near 7.0. Lime can also be added in the form of ground agricultural limestone ($CaCO_3$) (Lasdin and O'Neill 1994).

2.   According to Tchobanoglous, *et al.* (1977), the optimum temperature for biological stabilization is between 45° C and 55° C. For best results the temperature should be maintained between 50° C and 55° C for the first few days and between 55° C and 60° C for the remainder of active composting period. The temperature should not be allowed to go beyond 66° C, for odor control and to prevent high heat exposure of microbes.

3.   Range of values listed for this parameter are examples of specific values that were used successfully.

4.   In the nutrient balance, a carbon to nitrogen ratio should be below 30 in order to minimize the time required to digest the waste. As the carbon to nitrogen ratio increases, the composting process is prolonged and if it becomes greater than 80, the digestion process ceases to work.

4.11 CONTROLLED SOLID PHASE BIOLOGICAL TREATMENT (CSPBT)

Engineering Parameters	Range of Values	References
Matrix Characteristics		
Type of Contaminants	Mainly Organic	
Recommended Particle size	1 to 3 inches	
pH	5 - 9	McCoy and Associates; USEPA 1995a
Presence of Heavy Metal	Not Desirable	
Operating Parameters		
Moisture Content	50-60% (Optimum is 55%)	Findlay *et al.* 1994
Spacing of the PVC pipe for air distribution	2-inch slotted pipe at 10 feet	Murthy 1992
Height of the Soil Pile (Bioreactor Cell Height)	3 to 10 feet	McNicoll *et al.* 1995
Seeding and Mixing	1 to 5% (by weight) of partially decomposed solid waste or sewage sludge	Findlay *et al.* 1994; Tchbanoglous *et al.* 1977
Mixing Rate/Frequency	Once in seven days	Minier 1993; Findlay *et al.* 1994
Average Treatment Time	2 to 4 months	McNicoll *et al.* 1995
Temperature	45 - 70° C	Toomajian *et al.* 1993
Bulking Agents	Wood Chips or Animal/Vegetable Waste (for sludge; sludge to chips ratio = 3:2)	Cookson 1995
Rate of Volatilization of VOC vapors and Safety Issues	Treatment of vapor with activated carbon	
Monitoring - Sample Frequency	First month - weekly Second and Third months - Every two weeks After 3 months - Monthly	McNicoll *et al.* 1995

4.11 CONTROLLED SOLID PHASE BIOLOGICAL TREATMENT (continued)

Engineering Parameters	Range of Values	References
Nutrients	Commercial blend of slow-release nutrients (ammonium chloride and dipotassium phosphate)	
Carbon to Nitrogen Ratio before composting	35 to 50	Tchobanoglous *et al.* 1977
Carbon to Nitrogen Ratio after composting	7 to 20	Toomajian *et al.* 1993; Tchobanoglous *et al.* 1977
Air Exchange Rate	3 - 5 pore volumes/day	McNicoll *et al.* 1995
Air Flow Rate	127 scft/min	Murthy 1992

4.12   LANDFARMING[1]

Engineering Parameters	Range of Values	References
Matrix Characteristics		
Type of Contaminants	Organics (mainly petroleum hydrocarbons)	
Soil Classification	Medium to fine sand	
Presence of Heavy Metals	Not Desirable	
Moisture Content	60 to 90% of Field Capacity	Based on the design at Air Station Brooklyn, CEU Providence and Cookson 1995
Permeability	Blend till to a uniform mix	Cookson 1995
Cation Exchange Capacity of the Soil	3.1 - 9.1 meq/100 grams (average 5.2 meq/100 grams)	Based on the design at Air Station Brooklyn, CEU Providence
pH	5 - 9	McCoy and Associates; USEPA 1995a
Redox Potential	>800 mV	Cookson 1995
Operating Parameters		
Number of Lifts	Up to 3	USEPA 1995a
Mixing Rate/Frequency (Tilling)	Weekly - Typical	Cookson 1995
Type of Liner to Control Leachate	60 - 80 mil HDPE with 2 to 4 feet sand base	Cookson 1995
Residence Time	2 to 6 months	Cookson 1995
Temperature	60° C - 65° C	Worne and Fortune 1992
Oxygen:Chemical Oxygen Demand (O_2:COD)	3.5:1	
Space Needed/Soil Loading Rate	150 tons/acre/year	Worne and Fortune 1992
Minimum Soil Media Subbase above Liner	12 to 24 inches	Cookson 1995
Soil Lifts	4 to 24 inches	Cookson 1995
Monitoring Frequency	Weekly - Monthly	

4.12 LANDFARMING (continued)

Engineering Parameters	Range of Values	References
Biological Activities		
Type of Biological Activity	Aerobic	
Nutrients	3 pounds/yd^3 in single dose application	Cookson 1995
Carbon:Nitrogen:Phosphorus	100:10:1 (minimum)	University of Wisconsin 1993
Microbial Count (Hydrocarbon Utilizers)	4,400 - 36,000 cfu/gram (average 17,700 cfu/gr)	Based on the design at Air Station, Brooklyn, Providence CEU

FOOTNOTES - 4.12 LANDFARMING

1. The basic approach in aerobic bioremediation technologies - landfarming & surface treatment, in-situ treatment, biosparging/bioventing and bioreactors is similar. That is, oxygen, nutrients and bacteria generally are added to the system through site management techniques while temperature and moisture content are controlled to the extent possible (Pennington 1993).

4.13 SLURRY PHASE BIOLOGICAL TREATMENT[1]

Engineering Parameters	Range of Values	References
Matrix Characteristics		
Targeted Matrices and Contaminants	Soils, sludges, and groundwater contaminated by explosives, petroleum hydrocarbons, petrochemicals, solvents, pesticides, wood preservatives, and other organic chemicals	USEPA 1994b
Operating Parameters		
Solids in the Slurry	Typically 10 to 50% by weight	Zappa et al. 1993; USEPA 1994b; Jerger and Woodhull 1994
Type of Biodegradation	Typically aerobic (anaerobic is rarely practiced)	Zappa et al. 1993
Operating Temperature	15 to 40° C	
Oxygen Uptake Rate	0.3 - 0.5 mg/l/minute	Bergman et al. 1992 USEPA 1995a
Rate of Biodegradation[2]	Decay rates for PAH = 0.19 to 0.54 days^{-1}	Jerger and Woodhull 1994
Residence Time in the Bioreactor[3]	5 days to 11 months	
Minimum Oxygen Content for biodegradation	2 mg/l in the mixed Liquor	USEPA 1995a
Need for the Addition of Microorganisms	May be necessary if they are not naturally present	USEPA 1994b
Recommended Dewatering Devices to Dewater the Soil Slurry	Clarifiers, pressure filters, vacuum filters, sand drying beds, or centrifuges	USEPA 1994b
Microbial Plate Count	10^5 to 10^7 cfu/ml	USEPA 1995a
Nutrient Nitrogen Content	0.05 mg/l	USEPA 1995a
Nutrient Phosphorus Content	0.05 to 10 mg/l	USEPA 1995a

4.13 SLURRY PHASE BIOLOGICAL TREATMENT (continued)

Engineering Parameters	Range of Values	References
Removal Efficiency	Approximately 95% - 100%	USEPA 1994b; Chilcote and Sheehan 1992; Hartz and Beach 1992
Need for a Bench-Scale Study	Recommended	Zappa *et al.* 1993

FOOTNOTES - 4.13 SLURRY PHASE BIOLOGICAL TREATMENT

1. Soil washing and slurry-phase biodegradation are complimentary technologies from a process point of view, since soil washing removes the coarse soil particles that settle rapidly. Removal of this material prior to the slurry-phase process reduces energy requirements and operational problems (Chilcote and Sheehan 1992).

2. Based on a bench-scale and full-scale studies while remediating PAH-contaminated soil, Jerger and Woodhull (1994) reported that the majority of the (biodegradation about 95%) occurred during the initial 5 to 10 days of the total duration of 30 days.

3. Typical residence times for different contaminants are as follows (USEPA 1994b):

    PCP-contaminated soil   ==>   5 days
    Pesticide-contaminated soil ==>   13 days
    Refinery sludge   ==>   60 days

    While treating soil and sludge, the system was designed based on a residence time of 10 to 11 months (USEPA 1995a).

4.14 CHEMICAL REDUCTION/OXIDATION[1]

Engineering Parameters	Range of Values	References
Matrix Characteristics		
Types of Contaminants	Metals, Cyanides, etc.	
Operating Parameters		
Hydrogen Peroxide Application Rate[2]	3 to 50%	O'Brien and Gere 1995
Wavelength for Ultraviolet (UV) Radiation[3]	240-330 nm (many organics are oxidized at 254 nm)	O'Brien and Gere 1995; Lavid *et al.* 1994
Typical Reagent used in Reductive Dechlorination[3,4]	Alkali-Metal Hydroxide (such as KOH)	O'Brien and Gere 1995 Lavid *et al.* 1994

FOOTNOTES - 4.14 CHEMICAL REDUCTION/OXIDATION

1. Chemical reduction/oxidation (Redox) is a common treatment for cyanide wastes. The target contaminant group for chemical redox is inorganics (USEPA 1994b).

2. Hydrogen Peroxide (H_2O_2) is a nonviscous liquid that is used commercially in a diluted form of a 3 to 50% solution. H_2O_2 readily reacts with a wide variety of organic chemicals, both those with saturated and unsaturated carbon bonds. The ultimate products are carbon dioxide and water. Metals can be oxidized in a way similar to that of organic compounds. Under certain physical conditions, H_2O_2 acts as a reducing agent. At pH between 5 and 9, it reduces chlorine to the chloride ion. At a low pH, it reduces hexavalent chromium to the trivalent form. H_2O_2 has successfully treated soil contaminated with hydrocarbons (O'Brien and Gere 1995).

3 & 4. This information exists in O'Brien and Gere (1995). Waste streams containing chlorinated hydrocarbons can also be treated with *Reductive Photo-Dechlorination* process that uses UV light in a reducing atmosphere. However, this process has been used successfully to treat volatile chlorinated wastes in the liquid or gaseous phase (Lavid *et al.* 1994).

4.17   SOIL WASHING

Engineering Parameters	Range of Values	References
Matrix Characteristics		
Targeted Contaminants	Heavy metals, radionuclides, SVOCs, fuels, selected VOCs and pesticides	Fristad and Jones 1994
Type of Sand Preferred for this Treatment	Coarse sand and gravel	Frederick and Krishnamurthy 1994
Particle Size Distribution	0.24 to 0.20 mm is the optimum range	USEPA 1995e
Moisture Content	15%	USEPA 1995e
pH	Around 6.5	USEPA 1995e
Presence of Humic Content in the Soil	Needs Pretreatment	
Hydraulic Conductivity	Greater than 1×10^{-3} cm/second	USEPA 1991d
Total Organic Carbon	Should be less than 10% weight	USEPA 1995e
Cation Exchange Capacity	Should be less than 8 meq/l	USEPA 1995e
Operating Parameters		
Washing/Flushing Solvent Components/Additives[1]	Polymer and Surfactant	USEPA 1995e
Approximate Area Needed for a Mobile Unit	4 acres for a 20 ton/hour unit	USEPA 1990b
Net Quantity of Water Needed (water cleanup and recirculation)	130,000 - 800,000 gallons/cubic yards or 0.05 to 0.3 gallons per pound	USEPA 1990b
Soil Washing in Conjunction with Other Technologies[2]	With Activated carbon, biodegradation, or chemical precipitation to treat contaminated groundwater resulting from soil flushing	USEPA 1991d

4.17 SOIL WASHING (continued)

Engineering Parameters	Range of Values	References
Time Needed for Remediation	Less than 3 months for 20,000-ton site	USEPA 1994b
pH	7 to 10	
Liquid-to-soil Ratio	6:1 to 10:1	Cline and Reed 1995; Frederick and Krishnamurthy 1994
Size of the Soil Washer[3]	Varies. 20 to 25 tons/hr.	USEPA 1992c; USEPA 1995e
Aqueous Stream	Need Treatment	
Contaminant Removal Efficiency[4]	83% to 100%	Frederick and Krishnamurthy 1994; Pruijn 1994; Niaki and Kumar 1993; USEPA 1992c
Need for Dewatering[5]	Requirements vary	Eagle et al. 1993; Moore 1994

FOOTNOTES - 4.17 SOIL WASHING

1. In a study, Niaki and Kumar (1993) reported that the removal efficiency of pesticide increased with the use of surfactants. Some of these surfactants were SDS, Tergitol and Adsee.

2. X-ray fluorescence (XRF) instrument can be used on-site during the excavation activities and during the soil washing operation for the analysis of chromium, copper and nickel (USEPA 1995f).

3. While preparing a cost estimate for a full-scale soil washing system, USEPA (1992c) chose a Soil Washer of 20 ton/hour capacity coupled with 23 gpm Slurry Bioreactor and 100 gpm Fixed-film Biological Treatment System.

4. In a pilot study conducted by Frederick and Krishnamurthy (1994), pesticide reduction of 93 to 97 percent was observed where approximately 1 percent of surfactant was used to wash the contaminated soil. In another case study where soil washing included wet screening, hydrocycloning, gravity separation and froth flotation, the removal efficiency for PAH was reported to be 98% (Pruijn 1994). Niaki and Kumar (1993) reported a pesticide removal efficiency of 97-100%. USEPA (1992c) reported a PAH removal efficiency of as low as 83% and metal removal efficiency ranging from 50% to 70%.

4-25

FOOTNOTES - 4.17 SOIL WASHING (continued)

5.   For the contaminated soil fraction that requires transportation and subsequent disposal, dewatering is especially important in order to comply with disposal site moisture limits, as well as to lower the weight and volume of material. Particles larger than 4 mesh (4.75 mm) are relatively easy to dewater with vibrating screens (Eagle *et al.* 1993).

4.18   SOIL VAPOR EXTRACTION - Ex Situ

Engineering Parameters	Range of Values	References
Matrix Characteristics		
Types of Contaminants	Chlorinated Solvents, Petroleum hydrocarbons, SVOCs, VOCs, Pesticides	
Soil Classification[1]	Sandy thru silty/clay soil	USEPA 1991b
Air Permeability	$> 10^{-10}$ cm^2 (0.01 darcies)	
Porosity	0.25 (effective) typically assumed	Based on Base Miami Beach, design CEU Miami
Hydraulic Conductivity[1]	$>10^{-10}$ cm/sec.	USEPA 1995b
Moisture Content	<50%	
Depth to Water Table	>5 feet	
Henry's Constant of the Volatile Compounds[2]	> 0.001	O'Brien and Gere 1995
Operating Parameters		
Air Flow Rate[3]	35 to 400 cfm	Based on USCG Projects
	up to 4500 scfm or 136 sfm/well	USEPA 1995b
Half Lives for an Airflow of 3000 scfm[4]	PCA = 296 days PCE = 47 days TCE =50 days	USEPA 1995b
Operating Pressure/Vacuum	Up to 20" Hg	USEPA 1995b
Typical Diameter of the Extraction Well[5]	2 to 4 inches	
Typical Depth of Extraction Wells	Typical is 15 to 100 feet.	USEPA 1994b
Placement of the Screen[6]	Near the water table	
Treatment Required for Air emissions	Activated Carbon typically Biofilters are coming into use.	
Effectiveness	Not effective in the saturated zone	
Design Life of the SVE System	30 years	USEPA 1995b

FOOTNOTES - 4.18 SOIL VAPOR EXTRACTION

1. Clayey or silty soils may be effectively ventilated by the usual levels of vacuum developed in an SVE system (USEPA 1991b). Relationships between soil types, particle sizes, and hydraulic conductivity are presented in Figure 1 (Appendix A).

    SVE systems designed at this low hydraulic conductivity value (10^{-10} cm/sec) are high vacuum systems measuring vacuum in inches of mercury (Hg) typically using liquid ring pumps.

2. Henry's Constant is defined as the ratio of compound's concentration in air to that concentration in water (O'Brien & Gere 1995). According to USEPA (1991b and 1994b), this technology works well for volatile compounds with Henry's constant greater than 0.01 or a vapor pressure greater than 0.02 inches of mercury.

3. At Air Station Elizabeth City (CEU Cleveland), passive wind turbines were used. The flow rate varied from 4 to 61 cfm/wind turbine. USEPA (1995b) has reported the design airflow of up to 4500 scfm with 20 inches of mercury.

4. The half life for a given contaminant is the time required for half of the original amount to be removed from the unsaturated zone. For a given contaminant, the initial solvent removal rate is directly proportional to the air flow rate.

5. Both the inlet and injection wells are similar in design to the extraction wells, but they are smaller in diameter (O'Brien & Gere 1995)

6. The recovery rate of VOCs is higher if a section of the screen is placed near the water table rather than the entire depth of the well. Ensure that the screen height can accommodate the highest fluctuation of the watertable in order to have screen within the unsaturated zone under all conditions.

4.19 SOLIDIFICATION/STABILIZATION (S/S) - Ex Situ

Engineering Parameters	Range of Values	References
Matrix Characteristics		
Types of Contaminants[1]	Metals, PCBs, Oil sludges, Pesticides and organics (resins, etc.), Creosote wastes	USEPA 1990a
Concentration of Contaminants[1]	Varies for Contaminants	USEPA 1990a
Commonly Used S/S Systems[1]	Pozzolan-portland cement systems; Lime-fly ash pozzolan systems; Sorption; and Organic binding	USEPA 1990a
Hydraulic Conductivity (based on literature)	greater than 1×10^{-8} cm/sec	
Operating Parameters		
Percentage Binder Added[2]	5 to 35%	USEPA 1990a
Volume Increase	4 - 75%	USEPA 1990a; USEPA 1992a; USEPA 1992b
Increase in Density	0.6 to 11% (average is 5.5%)	USEPA 1992a
Soil Processing Capacity	40 to 80 tons per hour for shallow mixing; 20 to 50 tons per hour for deep mixing	
Minimum Unconfined Compressive Strength of the Soil after Treatment	50 pounds per square inch (according to USEPA guideline). A range of 75-866 psi has been in literature (average 410 psi)	McCoy and Associates 1992
Disposal Method	Generally on site. May also be in a landfill.	
Efficiency in Reducing the Mobility of Contaminated Waste	Greater than 95%	

FOOTNOTES - 4.19 SOLIDIFICATION/STABILIZATION (S/S) - Ex Situ

1. USEPA (1989a) reported the successful use of the HAZCON process in solidifying contaminated material high in organics (as high as 25%) that includes petroleum refinery waste stream. The HAZCON process is a cement-based process whose design concept is to solidify and immobilize waste contaminants. The principal difference between this process and other cement-based processes is the use of a proprietary component-Chloranan - which is claimed to permit solidification of waste materials with high organic concentrations. Immobilization of heavy metals (such as lead and zinc up to 2.3% by weight) in waste streams were successfully achieved.

    USEPA (1992a) reported the successful use of this technology for soil contaminated with pentachlorophenol (PCP) and arsenic.

2. Several case studies by USEPA (1990a) reported the amount of binder added ranging from 5% to 35% while immobilizing copper (2000 ppm), chromium (220 ppm), nickel (750 ppm), lead (2 to 100 ppm), aluminum (9500 ppm), PCBs (< 500 ppm), vinyl chloride, oil sludges, pesticides and creosote wastes. In one of the other case studies reported by USEPA (1989b), as much as 50% of binder addition has been reported (this may an exception to the range of 5% to 35%).

    In another case study where lead in the soil (80 to 120 mg/l), with an organic content of 17% was immobilized, several binder to soil ratios were successfully used (USEPA 1993b). See Table 4 in Appendix B for those ratios.

4.20 SOLVENT EXTRACTION[1]

Engineering Parameters	Range of Values	References
Matrix Characteristics		
Targeted Contaminants	Organic contaminants such as PCBs, VOCs, halogenated solvents and petroleum wastes	USEPA 1994b; USEPA 1994d
Soil Classification[2]	Clay less than 15%	USEPA 1995g
Optimal Moisture Content[2]	less than 20%	USEPA 1995g
Screening	Materials greater than 0.25 inch in diameter should be removed	Armstead *et al.* 1993; USEPA 1994d
Feed Material Size	6 to 76 mm	USEPA 1995g
pH	Greater than 10 has been reported	USEPA 1994d
Operating Parameters		
Approximate Area Needed for a Mobile Unit	300 square feet for small-scale, single extraction vessel configuration for treatability studies; and 4,000 square feet for larger operation	USEPA 1995g
Capacity of the Extraction Tanks	Varies. 16 to 17 cubic yards have been used.	USEPA 1995g
Solvents Used[3]	Propane, Triethylamine (TEA), sodium chloride	Markiewicz 1992; Jenkins *et al.* 1993
Solvent Extraction in Conjunction with Other Technologies	Solidification/Stabilization, Incineration or Soil Washing or can be a stand alone technology.	
Operating Temperature[4]	Ambient Temperature above freezing	
Amount of Solvent Needed	7 gallons of solvent per ton of soil	USEPA 1995g
Need for a Treatability Test	Typically needed	
Moisture Content in CF's Filtration System	40-60%	Markiewicz 1992
System Throughput for CF System	25 tons per day (continuous)	Markiewicz 1992
Contaminant Removal Efficiency[5]	Around 99%	Armstead *et al.* 1993

FOOTNOTES - 4.20 SOLVENT EXTRACTION

1. The solvent extraction process generally consists of three basic steps: (a) solvent washing, (b) solute contaminant removal from the extracting solvent, and (c) solvent recovery. Various types of solvent extraction units can be used, including (a) a single stage combination mixing/settling unit, (b) a multistage unit that uses counter current flow within a single device, or (c) several single stage units in series (Armstead *et al.* 1993).

   The Basic Extraction Sludge Treatment (B.E.S.T.®) solvent extraction process consists of primary extraction/dewatering, secondary extraction/solids drying, solvent storage, solvent separation, solvent recovery (USEPA 1994b).

   The CF Systems' solvent extraction process for the remediation of organic-contaminated soil and sludges includes: feed delivery system; extraction/gravity settling system; treated solids filtration system; solvent recovery system; and vent gas recovery system (Markiewcz 1992).

   More information on different types of solvent extraction is presented in Table 5 (Appendix B).

2. Contaminated soils with greater than 15% clays are difficult to treat because contaminants are strongly sorbed to the soil particles. Higher clay concentrations require additional wash cycles and physical handling to reduce clay aggregate size. Higher moisture content (more than 20%) requires soil drying and solvent distillation to reduce water accumulation in the solvent.

3. Different solvents have been used by different investigators. The solvents that have been tried include propane (Markiewicz 1992), Triethylamine in the B.E.S.T. process, and sodium chloride used in a DOD facility (Jenkins, *et al.* 1993).

4. Cold temperatures reduce solvent mobility (USEPA 1995). In the B.E.S.T.® solvent extraction process patented by the Resource Conservation Company (RCC), the solvent's temperature is maintained below 65°F, because triethylamine (TEA - the solvent) is completely soluble with water below 65°F, while above this temperature, the TEA and water are only partially miscible (Morin and Nickerson 1993). Note that TEA is highly flammable and requires a 100 feet radius control zone (USEPA 1995i).

5. Armstead *et al.* (1993) reported a removal efficiency of over 99% while treating organochlorine and other pesticides. Markiewicz (1992) reported a 99% of removal efficiency for dioxin, pentachlorophenols and PAHs in the CF System. Based on a bench-scale study Morin and Nickerson (1993) reported that CF's liquefied propane extraction process appeared to remove PCBs more efficiently in initial extraction stages compared to the Resource Conservation Company's process (B.E.S.T.®).

4.21 HIGH TEMPERATURE THERMAL DESORPTION

Engineering Parameters	Range of Values	References
Matrix Characteristics		
Target Contaminants	VOCs, SVOCs, PCB, PCP, PAH Mainly Petroleum Hydrocarbons	Horne and Jan 1993
Soil Classification	Medium to Fine Sand	
Moisture Content	< 20% to maintain efficiency	O'Brien and Rouleau 1993
Feed Particle Size	< 2 inches in diameter	USEPA 1994b; O'Brien and Rouleau 1993
Boiling Point for Compounds to be Removed[1]	Varies	O'Brien and Rouleau 1993
Operating Parameters		
Residence Time	5-60 minutes	O'Brien and Rouleau 1993
Feed System	Will consist of a screening device to separate and remove materials greater than 2 inches	
System Throughput	1 to 20 tons/hr	O'Brien and Rouleau 1993
Operating Temperature (Bed Temperature)	400-2200° F, determined by boiling point of contaminants	Li and Dodge 1993; Horne and Jan 1993; O'Brien and Rouleau - 1993; USEPA 1994c
Offgas Treatment	1) Wet Scrubbers or Fabric Filters Carbon 2) Adsorption System or Secondary Combustion 3) Chamber or Catalytic Oxidizer 4) Venturi Scrubbers	
Removal Efficiency	99% for hydrocarbons	Horne and Jan 1993
Need For a Treatment Study	Study Recommended	
Duration of Treatment	Over 4 months for 20,000-ton site	USEPA 1994b

FOOTNOTES - 4.21 HIGH TEMPERATURE THERMAL DESORPTION

1. Effective temperatures of HTTD are determined, among other parameters, by the boiling point of the contaminant to be removed from the soil (O'Brien and Rouleau 1993).

4.23 INCINERATION

Engineering Parameters	Range of Values	References
Matrix Characteristics		
Type of Contaminants	PCB is one of the common candidates	
Water Slurry Ratio[1]	4:1 to 8:1	Pfeiffer et al. 1993
Bulk Density	30-130 pounds/cubic foot	
Operating Parameters		
Residence Time	Approximately 15-60 minutes	USEPA 1989c; Mills *et al.* 1993
Feed System[1]	May consist of a screening device to separate and remove materials greater than 2 inches	Pfeiffer et al. 1993
Suggested Process Equipment Type	Rotary kiln, circulating fluidized bed, infrared	
System Throughput	Approximately 7-50 tons/hour	USEPA 1989c; Donnelly *et al.* 1992
Operating Temperature	800 - 2000° F	USEPA 1989c; Mills *et al.* 1993; Wells and Hodges 1994
Draft Capacity at Stack	1,000 cubic feet per minute	Wells and Hodges 1994
Offgas Treatment (Afterburner Temperature)	1550 - 1750° F	Pfeffer *et al.* 1993
Rate of Emission from the Bag House	7130 cubic feet/minute	Pfeffer *et al.* 1993
Speed of the Drum Rotation	0.5-6.0 rpm	Pfeffer *et al.* 1993
Contaminant Removal Efficiency	>99%	Donnelly *et al.* 1992

FOOTNOTES - 4.23 INCINERATION

1. Waste propellant is commonly ground and slurried with water prior to being fed to the incinerators. Water slurry ratios of 4:1 to 8:1 are typical for rotary kiln incinerators (Pfeffer *et al.* 1993).

4.24   LOW TEMPERATURE THERMAL DESORPTION

Engineering Parameters	Range of Values	References
Matrix Characteristics		
Type of Contaminant	Typically, Petroleum Hydrocarbons. Also includes VOCs, SVOCs, PCBs. This technology is applicable for the separation of organics from refinery wastes, coal tar wastes, wood-treating wastes, creosote - contaminated soils, radioactive wastes, synthetic rubber processing wastes, and paint wastes	USEPA 1991e
Soil Classification	Fine to Coarse Sand	
Minimum Solid Content in the Contaminated Medium	20 to 30%	USEPA 1991e
Acceptable Moisture Content	less than 20%	
pH of the Medium	5 - 11	USEPA 1991e
Operating Parameters		
Typical Space Requirements	50 feet x 150 feet	
Residence Time	Approximately 20 minutes	O'Brien and Gere 1995
Feed System	Will consist of a screening device to separate and remove materials greater than 1.5 inches	USEPA 1991e
Operating Temperature (Bed Temperature)	200 - 1000° F	USEPA 1991e
Process Equipment Types	Rotary dryer, asphalt plant aggregate dryers, thermal screw, conveyor furnace	Troxler *et al.* 1992
Draft Capacity at Stack	40,000 ft^3 per minute	O'Brien and Gere 1995
Offgas Treatment	Wet scrubbers or fabric filters Carbon Adsorption System or Secondary Combustion Chamber or Catalytic Oxidizer	
Rate of Emission from the Bag House	0.02 grain/dry standard cubic feet	USEPA 1995e
Dust Mitigation	Typically Water Spray	USEPA 1991e
Removal Efficiency for nonpolar halogenated aromatics (chlorobenzene)[1]	65 to 99%	Offutt and Knapp 1992
Typical Moisture Content in the Treated Medium	<1%	USEPA 1995e

FOOTNOTES - 4.24 LOW TEMPERATURE THERMAL DESORPTION

1. Approximate removal efficiencies based on bench-, pilot-, and full-scales have been demonstrated as follows (Offutt and Knapp 1992):

for polynuclear aromatics (naphthalene)	====>	65%
for other polar organics (acetone)	====>	82%
for nonpolar halogenated aromatics (chlorobenzene)	====>	99%

4.27   VITRIFICATION

Engineering Parameters	Range of Values	References
Matrix Characteristics		
Targeted Contaminants[1]	Inorganics (metals,radionuclides, etc.), Pesticides, PAHs, Dioxins	USEPA 1994b; USEPA 1995e
Hydraulic Conductivity	$<10^{-5}$ cm/sec.	Buelt *et al.* 1987
Moisture Content	<55%	USEPA 1994f
Alkaline Content	>1.4 % by weight	USEPA 1994f
Combustible Content	<7% by weight	Buelt 1992
Metals Content	<25% by weight	Buelt 1992
Operating Parameters		
Power Consumption	500 - 3,500 KW	USEPA 1994f
Types of Vitrification Processes	Electric Process Heating; and Thermal Process Heating	USEPA 1992d
Types of Electric Process Heating	Joule Heating (Ex situ and In situ); Plasma Heating[2]; and Microwave Heating	USEPA 1992d
Types of Thermal Process Heating[2]	Rotary Kiln Incineration (RKI); and Multi-fuel Glass Melter (MGM)	USEPA 1992d
Typical Size of a Melt Cell	26 ft x 26 ft and 19 feet deep	USEPA 1992d; USEPA 1994f
Typical and Duration for the Melt	10 to 20 days	USEPA 1995e
Electricity Consumed per Melt	559,200 - 1,100,000 KWH	USEPA 1995e
Duration for Cooling of Melts	Approximately One Year	USEPA 1995e
Melt Temperature in Joule Heating	1000° C - 1600° C	USEPA 1995e
Material Heated to Temperature in Plasma Heating	>1600° C	USEPA 1995e
Frequency for Microwave Heating	3,000 - 30,000 MHz	USEPA 1995e

4.27 VITRIFICATION (continued)

Engineering Parameters	Range of Values	References
Retention Time in RKI	Several minutes to one hour or more (up to 150 minutes)	USEPA 1995e
Temperature Maintained in RKI to Support Oxidation	1200° C	USEPA 1995e
Volume Reduction of the Soil Matrix	20 to 40%	O'Brien and Gere 1995; USEPA 1995e
Off-gas Treatment[3]	Organic off-gas needs to be controlled	USEPA 1992d
Removal Efficiency	99.99%	USEPA 1994f
Electrical (Ex Situ) (In Situ)	175 - 185 lb/hr 3 - 5 ton/hr	USEPA 1994f
Thermal - RKI	165 ton/day	USEPA 1994d
Plasma	0.5 ton/hour	Pacific Northwest Laboratory 1991

FOOTNOTES - 4.27 VITRIFICATION

1. In addition to the ones mentioned in the table, USEPA (1992b) has mentioned other wastes for vitrification: radioactive wastes and sludges; incinerator ashes; medical wastes; underground storage tanks; and asbestos wastes.

2. A plasma is an ionized gas. At high enough temperatures (e.g., 20,000° K for argon), electrons are stripped from their nuclei and the matter exists as a mixture of negative electrons, positive nuclei, and atoms. The ionized particles make plasma an excellent electrical conductor (USEPA 1992b). According to USEPA (1994d), in a plasma arc vitrification treatment system, waste material is fed into a sealed centrifuge where solids arc heated to approximately 3,200° F and gas temperature is maintained at a minimum of 1,800° F by a plasma torch. Organic material is evaporated and destroyed. Off-gasses travel through a gas-slag separation chamber to a secondary combustion chamber, where the temperature is maintained at over 2,000° F for about 2 seconds. The off-gasses then flow through an off-gas treatment system.

3. Common constituents in the off-gas streams are: metals; VOCs; SVOCs; particulates; sulfates and sulfur oxides; nitrogen compounds; carbon monoxide; and hydrogen halides and halogens.

4.29 NATURAL ATTENUATION[1] - SOIL (Intrinsic Remediation)

Engineering Parameters	Range of Values	References
Matrix Characteristics		
Soil Classification[2]	Soil with less clay (sandy soil)	
Moisture Content	25%-85%	Park and Sims 1994 University of Wisconsin 1995
Hydraulic Conductivity	$> 10^{-4}$ cm/sec	Testa 1995
pH[3,4]	5-9	McCoy and Associates 1992
Temperature[5]	4 - 40° C (optimum is 25 °C)	O'Brien and Gere 1995 Norris and Eckenfelder 1994
Depth of Soil Pile[5]	Shallow	Adriaens et al.. 1995
Maximum Depth to Contamination[5]	10 feet	Adriaens et al. 1995
Microbial Population Density	10^3 to 10^7 colony-forming units per gram	Leavitt 1992 Cleary 1995
Presence of Co-metabolite[6]	Varies	USEPA 1990a
Redox Potential[4]	pE + of 17.5 to 2.7	USEPA 1990a; USEPA 1994a; and Sawyer and McCarty 1985
Cation Exchange Capacity	Around 0.5 mhos/cm	
Types Contaminants	Organics	
Operating Parameters		
Intrinsic Permeabilities	$> 10^{-9}$ cm/day	Testa 1995
Process Involved in the Treatment	Biological Process	Currier et al. 1993
Type of Biodegradation	Mainly Aerobic	
Rate of Natural Attenuation	0.7 - 1.5 percent per day	O'Brien and Gere 1995
Nutrients - Carbon:Nitrogen:Phosphorus	100:10:1	Testa 1995
Oxygen Utilization Rates	0.02 to 0.99 percent oxygen/hour	Hinchee and Ong 1992
Minimum Oxygen Content for biodegradation	5 %	O'Brien & Gere 1995
The Need of a Conceptual Model Prior to Treatment	It is very important to have a model	

Summary of parameters for evaluation in consideration of Natural Attenuation as a remedial strategy is presented in Tables 6, 7, and 8 (Appendix B).

FOOTNOTES - 4.29 NATURAL ATTENUATION

1.   Natural attenuation is not a "technology" and is not the same as "no action," although it often is perceived as such. This approach is very suitable for low-risk sites. Natural attenuation describes monitoring and documenting the changes in concentration and distribution of contaminants over time as a result of the natural site conditions to which the contaminants are exposed in the absence of active remedial measures.

2.   Relationships between soil types, particle sizes, and hydraulic conductivity are presented in Figure 1 (Appendix A).

3.   Near-neutral pH values are most conductive to biodegradation. The pH can be increased using lime products, such as limestone, or it can be lowered with acidic materials.

4.   The pH (hydrogen ion activity) and pE (redox potential) of the geologic materials and the waste stream strongly influence contaminant mobility. The pH affects the speciation of many dissolved chemical constituents, which in turn determines solubility and reactivity. Ion exchange and hydrolysis reactions are also particularly sensitive to pH. pE influences many precipitation and dissolution reactions, particularly those involving iron and manganese, and determines in large measure the type of biodegradation that occurs.

     Redox potential is generally expressed in volts, E, or as the negative logarithm of the electron activity, pE. At neutral pH, aerobic conditions are associated with a pE of about 13, and anaerobic by pE below -3. For each unit decrease in pH, the respective values for pE increase about one unit.

5.   Cold temperatures and the depth of contamination inhibit biological degradation. If the depth of the soil that undergoes natural attenuation is deep, anaerobic conditions set in (Adriaens *et al.* 1995). Metabolic rate of the microorganisms reaches its maximum near 25° C (O'Brien & Gere 1995). According to Norris and Eckenfelder (1994), most aerobic biological-treatment processes operate within a temperature range of 4 to 39 ° C and they also mention that in cold climate areas the indigenous microorganisms are likely to be more active at the lower end of the acceptable temperature range than are bacteria indigenous to more temperate climates.

6.   Co-metabolism is defined as the biodegradation of an organic substance by a microbe that cannot use the compound for growth and hence must rely on other compounds for carbon and energy.

4.32 OXYGEN ENHANCEMENT WITH AIR SPARGING

Engineering Parameters	Range of Values	References
Matrix Characteristics		
Type of Contaminant	Hydrocarbons, TCE and PCE are good candidates	Hoekstra 1994
Soil Classification[1]	Silty sand to fine gravel	USEPA 1995h
Hydraulic Conductivity	$>10^{-4}$ cm/sec	USEPA 1993a
Depth to Groundwater	>5 feet favorable >3 feet unfavorable	USEPA 1993b; University of Wisconsin 1993
Clay Content	Presence of clay is not preferred	
Nonaqueous Phase Liquids	This technology may be used in conjunction with free product recovery	
Temperature[2]	4 - 40° C (Optimum is 25° C)	O'Brien and Gere 1995; Norris and Eckenfelder 1994
pH[3]	5 - 9	McCoy and Associates 1992; USEPA 1995a
Microbial Population Density	10^3 x 10^7 colony-forming units per gram	Leavitt 1992; Cleary 1995
Presence of Co-metabolite[4]	Varies	USEPA 1990a
Cation Exchange Capacity	Around 0.5 mhos/cm	
Operating Parameters		
Combination of Technologies[6]	SVE or Bioventing	USEPA 1994e
Well Spacing	10 to 15 feet	Piniewski *et al.* 1992
Depth of the Sparging Wells	10 feet below the dynamic water table	Piniewski *et al.* 1992
Sparging Well Information	Can be constructed of 2-inch PVC pipe with a 2-foot screen	Piniewski *et al.* 1992
Oxygen Utilization Rates	0.02 to 0.99 percent oxygen/hour	Hinchee and Ong 1992
Rate of Biodegradation	0.4 to 19 mg/kg	Hinchee and Ong 1992
Minimum Oxygen Content for biodegradation	5%	O'Brien & Gere 1995

Engineering Parameters	Range of Values	References
Microbial Activity - Oxygen Uptake Rate	Hydrocarbon:Oxygen=1:3.0 to 1:3.5	Makdisi et al. 1993; and Norris and Eckenfelder 1994
Microbial Activity - Carbon Dioxide Evaluation	0.05 - 9.1%	Based on USCG Project at Air Station Sitka, AK CEU Juneau
Treatment of Vapors[7]	Depends on the Regulatory Requirement	USEPA 1994e

FOOTNOTES - 4.32 OXYGEN ENHANCEMENT WITH AIR SPARGING

1.   Relationships between soil types, particle sizes, and hydraulic conductivity are presented in Figure 1 (Appendix A).

2.   Bioremediation can occur over the 15 - 45° C temperature range, but is most effective over the 20° C - 40° C (Autry and Ellis 1993). Metabolic rate of the microorganisms reaches its maximum near 25° C (O'Brien & Gere 1995). According to Norris and Eckenfelder (1994), most aerobic biological-treatment processes operate within a temperature range of 4 to 39 ° C and they also mention that in cold climate areas the indigenous microorganisms are likely to be more active at the lower end of the acceptable temperature range than are bacteria indigenous to more temperate climates. Cold temperatures and the depth of contamination inhibit biological degradation. If the depth of the soil that undergoes bioremediation is deep, anaerobic conditions set in (Adriaens *et al.* 1995).

3.   The pH affects the speciation of many dissolved chemical constituents, which in turn determines solubility and reactivity. Ion exchange and hydrolysis reactions are also particularly sensitive to pH. Near-neutral pH values are most conductive to biodegradation. The pH can be increased using lime products, such as limestone, or it can be lowered with acidic materials.

4   Co-metabolism is defined as the biodegradation of an organic substance by a microbe that cannot use the compound for growth and hence must rely on other compounds for carbon and energy.

5.   Where vertical air flow is restricted as a result of the presence of less permeable strata, sparging can push contaminated groundwater away from the injection point. In these cases, a groundwater recovery system or SVE system may be needed (USEPA 1994b).

6.   This process (in combination with SVE) generates one major wastestream-vapors from the vacuum extraction wells. Depending upon regulatory requirements, the extracted air may be treated above ground or released directly to the atmosphere (USEPA 1994e). USCG recommended procedure for evaluating the vapor treatment process is as follows:

        1. conduct analysis of vapors expected
        2. consult the appropriate regulatory agency
        3. design and install vaper treatment system if necessary

4.33 OXYGEN ENHANCEMENT WITH HYDROGEN PEROXIDE[1]

Engineering Parameters	Range of Values	References
Matrix Characteristics		
Type of Contaminant	VOCs, SVOCs and fuels	
Soil Classification[2]	Silty sand to fine gravel	USEPA 1995h
Hydraulic Conductivity	$>10^{-4}$ cm/sec	USEPA 1993a
Depth to Groundwater	Approximately 3-5 ft	USEPA 1993a; University of Wisconsin 1993
Nonaqueous Phase Liquids	This technology may be used in conjunction with free product recovery	Nelson et al. 1996
Temperature[3]	5 - 45° C (Optimum is 25° C)	USEPA 1992e
pH of the Sub-surface Material[4,5]	5.5 - 8.5	USEPA 1992e
Dissolved Oxygen Content of Water	> 2 mg/L	USEPA 1992e
Redox Potential [4]	> 50 mV	USEPA 1992e
Microbial Population Density	10^3 x 10^7 colony-forming units per gram	Leavitt 1992 Cleary 1995
Presence of Co-metabolite[6]	Varies	USEPA 1990a
Cation Exchange Capacity	Around 0.5 mhos/cm	
Operating Parameters		
Hydrogen Peroxide Dosage	100 mg/l	Goltz et al. 1995
	230 mg/l	Nelson et al. 1995
Recommended Concentration of H_2O_2 in water[7]	< 100 ppm	USEPA 1994b
Rate of H_2O_2 Application	100 - 1000 ppm	USEPA 1993a
Combination of Technologies	Air stripping or carbon adsorption or SVE or Phase Separation	USEPA 1994b; Nelson et al. 1996
Well Spacing	Depends on the plume	
Contaminant Removal Efficiency	Very efficient	
Treatment of Vapors	Depends on the Regulatory Requirement	
Nutrient Information C:N:P	100:10:1 to 500:10:1	USEPA 1992e; USEPA 1993a
Type of Biodegradation	Generally Aerobic	
Oxygen Utilization Rates	0.02 to 0.99 percent oxygen/hour	Hinchee and Ong 1992
Rate of Biodegradation	0.4 to 19 mg/kg	Hinchee and Ong 1992

4.33 OXYGEN ENHANCEMENT WITH HYDROGEN PEROXIDE (continued)

Engineering Parameters	Range of Values	References
Minimum Oxygen Content for biodegradation	5%	O'Brien & Gere 1995
Microbial Activity - Oxygen Uptake Rate	Hydrocarbon:Oxygen=1:3.0 to 1:3.5	Makdisi *et al.* 1993; and Norris and Eckenfelder 1994
Microbial Activity - Carbon Dioxide Evaluation	0.05 - 9.1%	Based on USCG Project at Air Station Sitka, AK CEU Juneau

FOOTNOTES - 4.33 OXYGEN ENHANCEMENT WITH HYDROGEN PEROXIDE

1. Hydrogen peroxide can be used as an oxygen source to support the growth and energy requirements of a native population of microorganisms (Goltz *et al.* 1995).

2. Relationships between soil types, particle sizes, and hydraulic conductivity are presented in Figure 1 (Appendix A).

3. Biodegradation can occur over the 15 - 45° C temperature range, but is most effective over the 20° C - 40° C (Autry and Ellis 1993). Metabolic rate of the microorganisms reaches its maximum near 25° C (O'Brien & Gere 1995). According to Norris and Eckenfelder (1994), most aerobic biological-treatment processes operate within a temperature range of 4 to 39 ° C and they also mention that in cold climate areas the indigenous microorganisms are likely to be more active at the lower end of the acceptable temperature range than are bacteria indigenous to more temperate climates. Cold temperatures and the depth of contamination inhibit biological degradation. If the depth of the soil that undergoes bioremediation is deep, anaerobic conditions set in (Adriaens *et al.* 1995).

4. The pH (hydrogen ion activity) and pE (redox potential) of the geologic materials and the waste stream strongly influence contaminant mobility. The pH affects the speciation of many dissolved chemical constituents, which in turn determines solubility and reactivity. Ion exchange and hydrolysis reactions are also particularly sensitive to pH. pE influences many precipitation and dissolution reactions, particularly those involving iron and manganese, and determines in large measure the type of biodegradation that occurs.

    Redox potential is generally expressed in volts, E, or as the negative logarithm of the electron activity, pE. At neutral pH, aerobic conditions are associated with a pE of about

13, and anaerobic by pE below -3. For each unit decrease in pH, the respective values for pE increase about one unit.

5. Near-neutral pH values are most conductive to biodegradation. The pH can be increased using lime products, such as limestone, or it can be lowered with acidic materials.

6. Co-metabolism is defined as the biodegradation of an organic substance by a microbe that cannot use the compound for growth and hence must rely on other compounds for carbon and energy.

7. USEPA (1994b) reports that concentrations of H_2O_2 greater than 100 to 200 ppm in groundwater are inhibiting to microorganisms.

4.34 AIR SPARGING

Engineering Parameters	Range of Values	References
Matrix Characteristics		
Type of Contaminant	VOCs and fuels	Hoekstra 1994; USEPA 1995h
Soil Classification[1]	Silty sand to fine gravel	USEPA 1995h
Hydraulic Conductivity	$>10^{-4}$ cm/sec	USEPA 1993a
Nonaqueous Phase Liquids	This technology may be used in conjunction with free product recovery	
Temperature	4 - 40° C (Optimum is 25° C)	O'Brien and Gere 1995; Norris and Eckenfelder 1994
pH	6 - 9	McCoy and Associates 1992
Dissolved Oxygen Content of Water	>0.2 mg/L	USEPA 1995h
Depth to Groundwater	Approximately 3-5 ft	USEPA 1993a; University of Wisconsin 1993
Henry's Constant of the Contaminant[2]	$>10^{-5}$ atm-m^3/mole	
Vapor Pressure of the Contaminant[3]	>1 mm of mercury	Angell *et al.* 1992
Type of Contaminant	VOCs and fuels	Hoekstra 1994; USEPA 1995h
Contaminant's Volatility	>5 mm Hg	USEPA 1993a
Contaminant's Solubility	<20,000 mg/l	USEPA 1993a
Operating Parameters		
Air Flow Rate	1 to 16 cfm per injection point	USEPA 1992f; USEPA 1995h
Ratio of extracted air to injected air	>4:1 (optimum is 5:1)	USEPA 1992f
Radius of Influence[4]	10 to 300 feet from the Injection Point	Noonan *et al.* 1993
Combination of Technologies	with vapor extraction	
Well Spacing	10 to 30 feet (10 to 15 feet is common)	Piniewski *et al.* 1992; USEPA 1992f
Depth of the Sparging Wells	Varies. 10 to 18 feet below the dynamic water table are reported. 10 ft minimum, <30 feet below water table	USEPA 1993a

4.34   AIR SPARGING (continued)

Engineering Parameters	Range of Values	References
Sparging Well Information	Can be constructed of 2-inch PVC pipe with a 2-foot screen. Screen length may vary from 2 to 10 feet.	
Application Air Pressure	1 psi for every 2.3 feet of water column depth above the injection screen	Raymond *et al.* 1994
Contaminant Removal Efficiency and Timing	90%	Hinchee, 1994
Contaminant's Biodegradability	$BOD_5 > 0.01$ mg/l BOD_5:ThOD > 0.001	USEPA 1993a
Treatment of Vapors	Depends on Regulatory Requirement. If needed, GAC can be used	

FOOTNOTES - 4.34 AIR SPARGING

1.   Relationships between soil types, particle sizes, and hydraulic conductivity are presented in Figure 1 (Appendix A). Sparging is very sensitive to the geological structure of subsurface soils. One must be aware of soil layers impervious to air flow which may direct the air away from the contaminated site.

2.   Henry's Constant is defined as the ratio of compound's concentration in air to that concentration in water (O'Brien & Gere 1995). Henry's constants for selected constituents are presented in Table 3 (Appendix B). Details of Henry's constants for various contaminants are also presented in Figure 2 (Appendix A).

3.   The vapor pressure of a compound is the pressure of its vapor in equilibrium with its pure liquid or solid phase. Vapor pressure increases with temperature. The vapor pressure at 40° F and maximum extraction rates of some common VOCs are presented in Table 9 (Appendix B).

4.   An effective radius of influence ranges from 10 - 30 feet, sometimes 50 feet. Influence distances greater than this likely indicate preferential flow paths and not a true radius of influence.

4.36 DUAL PHASE EXTRACTION

Engineering Parameters	Range of Values	References
Matrix Characteristics		
Soil Classification[1]	Heterogeneous clays and fine sands	USEPA 1991b USEPA 1994b
Target Contaminants	VOCs and fuels	USEPA 1994b
Approximate Volume of Contaminants in the Soil	55% of the pore volume	McCoy and Associates 1992
Air Permeability for Vapor Extraction Process	$> 10^{-10}$ cm^2 (0.01 darcies)	USEPA 1995b
Operating Parameters		
Air Flow Rate	100 cfm	Kikkeri et al. 1994
Operating Vacuum	Up to 29 inches of mercury	Kikkeri et al. 1994; Costa 1992
Typical Diameter of the Extraction Well	2 to 4 inches	O'Brien and Gere 1995
Placement of the Screen[2]	Near the water table	Trowbridge and Ott 1992
Spacing of Wells	40 feet	Trowbridge and Ott 1992
Combination with Other Technologies	Bioremediation, air sparging, bioventing, or pump-and-treat technologies	USEPA 1994b
Treatment Required for Water	Pump-and-treat technologies or bioremediation	USEPA 1994b
Treatment Required for Air Emissions[3]	Activated Carbon, Catalytic Oxidizer	Trowbridge and Ott 1992
Need of a Pilot Test	Recommended	

FOOTNOTES -4.36 DUAL PHASE EXTRACTION

1. Clayey or silty soils may be effectively ventilated by the usual levels of vacuum developed in a vapor extraction system (USEPA 1991b). Dual phase extraction system is more effective than SVE for heterogeneous clays and fine sands (USEPA 1994b). Relationships between soil types, particle sizes, and hydraulic conductivity are presented in Figure 1 (Appendix A).

2. The recovery rate of VOCs is higher if a section of the screen is placed near the water table rather than the entire depth of the well. In a case study, screened intervals extended up to 10 feet - 50 feet below ground surface. The screened interval selection was based on two criteria. The first criterion was that the screen must be placed so that the saturated zone could be fully dewatered using dual extraction. The second criterion was that the screen interval must adequately remediate the areas of highest hydrocarbon concentrations, as measured by organic vapor monitor reading taken during drilling (Trowbridge and Ott 1992).

3. In a case study where a catalytic oxidizer was used, it was capable of treating up to 1,000 scfm of vapors with a destruction efficiency of 99.8% and was capable of destroying up to 960 pounds of VOCs per day (Trowbridge and Ott 1992).

4.37 FREE PRODUCT RECOVERY[1]

Engineering Parameters	Range of Values	References
Matrix Characteristics		
Thickness of the Floating Hydrocarbon Lens	This method is generally applicable if it is 8" or more	USEPA 1994b
Separation Technique and Operating Parameters		
Skimmers - Used in trenches and the pump is located at the ground surface. Can be used where the hydraulic conductivity, K of the aquifer is low (approximately 10^{-5} cms/sec) and water table fluctuations are large.	Works well where the depth to groundwater is less than 25 feet.	
Filter Separators - Used in Trenches. Pump is located at the ground surface. May be used in conjunction with a dual pump system in shallow recovery wells. Works well for $K = 10^{-5}$ to 10^{-2} cms/sec.	Works well where the depth to groundwater is less than 25 feet	
Single Pump System - Useful for small spills with a submersible or surface pump	Recovery rates are less than 500 gallons/hour	
Combination of Technologies	Groundwater extraction with GAC is common	USEPA 1995h
Above Ground Oil/Water Separators - Useful when single pump system is used. Contaminant levels can be reduced to approximately 15 ppm.	Capacity of the separator is 10 times the volume of mixture to be treated per minute. Optimum residence time for separation is 10 to 12 minutes.	USEPA 1995h
Disposal of the Product	Water and product can be separated by gravity prior to disposal or recycling of the product	
Disposal Method of Water	On-site water treatment such as carbon adsorption is normally required	Hayes *et al.* 1989
Product Removal Efficiency[2]	25% of the Initial spill volume	USEPA 1992e

FOOTNOTES - 4.37 FREE PRODUCT RECOVERY

1.   Two approaches for the recovery of free product from an UST release are: trenches (passive trenches/drains and active trench system/sumps) and extraction wells (USEPA 1992e). Usually, treatment of coproduced groundwater during hydrocarbon recovery operations will include, as a minimum, oil/water separation to remove the free-phase hydrocarbons (Stover 1989).

2.   No free product recovery system can recover 100% of the release once it is in the soil system. In 4 case studies examined, an average recovery of 25% of the initial spill volume was observed. For the separation techniques, filters and product pumps are capable of reducing product thickness to a sheen, and above ground oil/water separators, are capable of reducing petroleum concentrations to approximately 15 ppm (USEPA 1992e). The actual results of oil/water seperators depends on the capacity of seperator and the types of contaminant.

4.41 SLURRY WALLS

Engineering Parameters	Range of Values	References
Parameters to Construct a Slurry Wall		
Where to use Slurry Wall?	Where the waste mass is too large for treatment and where soluble and mobile constituents pose an imminent threat to a source of drinking water	
Any Technology in Combination with Slurry Wall	Often used in conjunction with capping	
Efficiency in Containing Uncontaminated Water	95%	USEPA 1994b
What are Slurry Walls Constructed of?	Soil, bentonite, and water mixture; and also sheet piling, cement, bentonite and water	USEPA 1994b
Depth of Slurry Wall	Typically < 50 feet	USEPA 1994b
Thickness of Slurry Wall	2 to 4 feet	USEPA 1994b
Depth of Penetration of Slurry Wall into the Low Permeable Layer such as Clay or Bedrock[1]	2 to 3 feet	USEPA 1994b
If the Contaminants are Acids, Bases, Salt Solutions, and Some Organic Chemicals, how to make the Slurry Wall Withstand?	Other slurry mixtures can be developed to resist specific chemicals	USEPA 1994b

FOOTNOTES - 4.41 SLURRY WALLS

1. This "keying-in" provides for an effective foundation with minimum leakage potential. An alternate configuration for slurry wall installation is a "hanging" wall in which the wall projects into the groundwater table to block the movement of lower density or floating contaminants such as oils, fuels, or gases. Hanging walls are used less frequently than keyed-in walls.

4.43 BIOREACTORS

Engineering Parameters	Range of Values	References
Matrix Characteristics		
Temperature	4 -39° C	Autry and Ellis 1993; O'Brien and Gere 1995; Norris and Eckenfelder 1994
Type of Contaminants[1]	SVOCs, VOCs, Petroleum Hydrocarbons, PCP	USEPA 1994a; USEPA 1994d
Total Organic Content		
Operating Parameters		
Types of Processes	Fixed film reactors are commonly used	
Type of Degradation	Aerobic	McCoy and Associates 1992
Need for a Treatability or Feasibility Test	Bench or pilot scale study is highly recommended	
Power Usage for Pumping and Agitation in a Continuous Stirred Reactor	20 kw (typical)	
Salt Tolerance	The current bioreactor is able to process salt solutions having nitrate concentrations up to 300,000 ppm	
Size of the Bioreactor	100 m^3 of bioreactor was reported to be used for a demonstration	USEPA 1994d
Contaminant Removal Efficiency[2]	>80%	
End products	CO_2 and water	
Nutrient Ratio Carbon:Nitrogen:Phosphorus	100:5:1	Nyer 1993

FOOTNOTES - 4.43 BIOREACTORS

1. Bioreactors are used primarily to treat SVOCs, petroleum hydrocarbons, and biodegradable organic material. The process is less effective for some pesticides. (USEPA 1994a). However, according to USEPA (1994d), water contaminated with pentachlorophenol, creosote components, and phenols can also be treated in a bioreactor.

2. In general, 1000 ft^3 of media will remove 60 pounds of organics per day (Nyer 1993).

4.44 AIR STRIPPING

Engineering Parameters	Range of Values	References
Matrix Characteristics		
Type of Contaminant	Mainly VOCs SVOCs have also been removed	
Concentration of Contaminant	< 0.01 percent	USEPA 1991f
pH	5 - 11	USEPA 1995h
Henry's Constant of the Contaminant	> 0.01 atmospheres - m^3/mol	USEPA 1994b; USEPA 1991f
Presence of Inorganics[1]	Presence of high inorganics is not recommended	USEPA 1994b; Hammick and Iadarola 1992
Hardness	<500 mg/L	Nyer 1993
Iron	<5 mg/L	Nyer 1993
Degradable organics	<10 mg/L	Nyer 1993
Operating Parameters		
When to Choose a Pump-and-Treat Technology?	See the attached figure (Figure 3 in Appendix A)	
Height of Aeration Tank	Around 6 feet	USEPA 1994b
Height of Packed Towers	15 to 40 feet	USEPA 1994b
Type of Operation	Can be continuous or in a batch mode	
Capacity of the Pump (Groundwater pump plus the discharge pump)	0.33 to 2 HP for a flow of 1-20 gpm 1 to 5 HP for a flow of 20 - 75 gpm 5 to 30 HP for a flow of 100 - 600 gpm	USEPA 1994b
Capacity of the Pump (for the blower)	1.5 HP per foot of air stripper diameter (a rough rule of thumb)	USEPA 1994b
Combination of Technologies	Carbon adsorption or other appropriate technology	
Off-gas Treatment	Carbon adsorption, catalytic oxidation, thermal incineration or Photocatalytic oxidation is also used	Raupp *et al.* 1994

4.44   AIR STRIPPING (continued)

Engineering Parameters	Range of Values	References
Air:Water Ratio in a Packed Tower	10:1 to 300:1	USEPA 1995h
Operating Temperature[2]	Ambient	USEPA 1991f
Contaminant Removal Efficiency	Greater than 98% for VOCs Greater than 80% for SVOCs	USEPA 1991f; USEPA 1992e; USEPA 1994b
Capacity of the Air Stripper	Up to 2500 gpm is reported	USEPA 1995h
Duration for the Treatment	3 to 10 years	USEPA 1993d
Sources of Fouling	Iron, hardness, bacteria $(Fe^{+3,} Fe^{+2,} Fe(OH)_3)$	Nyer 1993
Air Stripper Types	packed towers cooling towers diffused aeration tanks	Nyer 1993
Water Outlets	screen w/24 mesh screening	Nyer 1993
Rules of Thumb	liquid loading rate 20 gpm/ft^2 of cross sectional area packing size; tower diameter ratio 1:6	Nyer 1993

FOOTNOTES - 4.44   AIR STRIPPING

1.   Presence of inorganics in high concentrations (e.g., iron greater than 5 ppm, hardness greater than 800 ppm) will affect the equipment with the problem of "fouling" (USEPA 1994b).

Almost all air strippers installed in the northeast have the same problem - iron bacterial fouling of pumps, well screens, and packing. One of the best ways to combat iron bacteria is to install pumps in such a way that they can be easily removed for cleaning. The wells should be large enough so that chemicals to kill bacteria can be added easily (if allowed by the regulatory agency). If proper access ports and drains are installed, chemicals can be added to the air stripping system to clean the packing on a regular basis. In the absence of drains, the packing must be replaced as needed (Hammick and Iadarola 1992).

2.   Air stripping is typically performed at ambient temperature. In some cases, the feed stream temperature is increased in a heat exchanger. Heating the influent liquid increases air-stripping efficiency and has been used to obtain a greater removal of SVOCs such as ketones (USEPA 1991f).

4.47 LIQUID-PHASE CARBON ADSORPTION[1]

Engineering Parameters	Range of Values	References
Treatment Characteristics		
Suspended Solids Concentration	< 50 mg/l	
Oil and Grease	< 10 mg/l	
Type of Contaminants Treated	SVOCs and Explosives	USEPA 1994b
Contaminants Which Cause Limitations	Metals and other suspended solids, Oil and Grease	
Total Organic Carbon Concentration	High levels of organic carbon (1000 mg/l) may result in rapid exhaustion of carbon	
Fulvic and Humic Acids	10-100 mg/l	
Molecular Weights of the Compounds that have the Proper Adsorption Properties	50 - 200 grams/gram-mol	
pH	Compounds are better adsorbed at high pH (>7)	
Maximum Inorganics Concentration	1000 ppm	
Solubility of Contaminants in Water[2]	The less soluble an organic compound is in water, the better it is adsorbed from the solution	Montgomery 1985
Operating Parameters		
Common Types of Designs	1. Fixed Bed 2. Pulsed or Moving Bed	USEPA 1994b
System Configuration[3]	varies	
Surface Area of the Carbon	500-2000 m^2/g	
GAC bed life	< 6 months for stringent objectives (C_e/C_i < 0.05)	
Adsorption Efficiency[4]	1 gram of VOC (or hazardous air pollutant) per 10 grams of Carbon	
Onsite reactivation of GAC Contaminant	Not economical unless more than 2,000 pounds per day of GAC are required to be reactivated	
Residence Time	15 minutes minimum	Nyer 1993
Disposal of GAC	If carbon cannot be economically reactivated, it must be discarded and may have to be treated and disposed of as a hazardous waste	

4.47 LIQUID-PHASE CARBON ADSORPTION (continued)

Engineering Parameters	Range of Values	References
Flow Rate[3]	0.5 to 1 gpm	USEPA 1994b
Pilot Test (Isotherm Test)	May be necessary	
Use of Regenerated Carbon	Regenerated carbon will have a lower Adsorptive Capacity.	
Removal Efficiency	70 - 99%	
Carbon Efficiency	C_e/C_i should be less than 0.3 to 0.5	USEPA 1994b

FOOTNOTES - 4.47 LIQUID-PHASE CARBON ADSORPTION

1. In liquid-phase carbon adsorption, activated carbon is used to remove unpleasant odors, tastes, or contaminants from a water stream passed through it. The undesirable compounds adsorb to the surface of the activated carbon. When the carbon source is exhausted, the carbon is removed and can be reactivated, regenerated, or discarded (USEPA 1991g).

   Liquid phase carbon adsorption is effective for removing contaminants at less concentrations (<10 mg/L) from water at nearly any flow rate, and for removing higher concentrations of contaminants from water at low flow rates (0.5 to 1 gpm) (USEPA 1994b).

2. Solubility information for specific organic compounds is presented in Table 10 (Appendix B).

3. When bed life is longer than 6 months and treatment is stringent, a single absorber is used. When less stringent objectives are required, blending of effluents from partially saturated adsorbers can be used to reduce carbon replacement frequency. When stringent treatment objectives are required and bed life is short, multiple beds in series may be used to decrease carbon usage rate (USEPA 1994b; USEPA 1991g).

4. Adsorption capacities for specific organic compounds are mentioned in Table 11 (Appendix B). However, in general, to remove one pound of contaminant, 5 to 20 pounds of carbon are needed (Nyer 1993).

4.49 ULTRAVIOLET (UV) OXIDATION

Engineering Parameters	Range of Values	References
Matrix Characteristics		
Targeted Contaminants	Petroleum hydrocarbons; chlorinated hydrocarbons; and ordnance compounds such as TNT, RDX, and HMX	USEPA 1994b
pH	4 to 9	O'Brien and Gere 1995
Presence of Heavy Metal Ion	Water should be relatively free of heavy metals. Should not be >10 mg/l. Pretreatment increases the efficiency.	USEPA 1994b; Kodukula 1992
Insoluble Oil or Grease	Water should be relatively free of this	USEPA 1994b
Operating Parameters		
Mode of UV Process	Batch or Continuous mode	USEPA 1994b
Contaminant Destruction Efficiency[1]	> 90%	USEPA 1990d
Need for Off-gas Treatment	Needed for volatile organics such as TCA which be volatilized (stripped) rather than destroyed	USEPA 1994b
Need for Pretreatment	May be required to minimize ongoing cleaning and maintenance of UV reactor	USEPA 1994b
Treatability Study	Recommended	O'Brien and Gere 1995
System Throughput	Can be as high as 1,000 to 1,000,000 gal/day Can be as low as 5 gpm	USEPA 1994b; Giggy 1994
Wavelength & Electrical Energy of UV Radiation in the Ultrox System (US)	Wavelength = 254 nm Electrical Energy = 65 to 15,000 W	O'Brien and Gere 1995
UV Lamp in *perox-pure* ™ System	5 kW UV lamp/sub-chamber the chamber 5 ft long x 3 ft wide x 7 ft high is divided 6 horizontal sub-chambers.	USEPA 1994b

4.49 ULTRAVIOLET (UV) OXIDATION (continued)

Engineering Parameters	Range of Values	References
Average Ozone Concentration in the US	2%	O'Brien and Gere 1995
Hydrogen Peroxide in the US	50% (Typical)	O'Brien and Gere 1995
Operating Temperature in the US	Aqueous Waste Stream = Ambient Ozone Destruction System = 60° C	O'Brien and Gere 1995
Residence Time in the US	2 to 60 minutes	O'Brien and Gere 1995 Kodukula 1992

FOOTNOTES - 4.49 ULTRAVIOLET (UV) OXIDATION

1. The Ultrox system achieved removal efficiencies as high as 90% for the total VOCs present in the groundwater. The removal efficiencies for TCE were greater than 99 percent. However, the maximum removal efficiencies for 1,1-dichloroethane (1,1-DCA) and 1,1,1-trichloroethane (1,1,1-TCA) under optimal operating conditions were about 65% and 85% respectively (USEPA 1990d).

4.50 NATURAL ATTENUATION[1] - WATER (Intrinsic Remediation)

Engineering Parameters	Range of Values	References
Matrix Characteristics		
Soil Type	Clayey Soil	
pH	5 - 9	McCoy and Associates 1992; USEPA 1995a
Temperature	4- 40° C (optimum is 25°C)	O'Brien and Gere 1995; Norris and Eckenfelder 1994
Type of Contaminants	Organics	
Maximum Depth to Water Table[2]	10 feet	Adriaens, et al. 1995
Microbial Population Density	10^3 to 10^7 colony-forming units per gram	Leavitt 1992; Cleary 1995
Presence of Co-metabolite	Varies	USEPA 1990a
Redox Potential[3]	pE + of 17.5 to 2.7	USEPA 1990a; USEPA 1994a; and Sawyer and McCarty 1985
Cation Exchange Capacity	Around 0.5 mhos/cm	
Dissolved Oxygen	> 1 - 2 mg/l	Testa 1995
Operating Parameters		
Process Involved in the Treatment	Biological Process	
Type of Biodegradation[4]	Mainly Aerobic	
Rate of Natural Attenuation	0.7 - 1.5 percent per day	O'Brien and Gere 1995
Nutrients - Carbon:Nitrogen:Phosphorus	100:10:1	Testa 1995
Oxygen Utilization Rates	0.02 to 0.99 percent oxygen/hour	Hinchee and Ong 1992
Minimum Oxygen Content for biodegradation	5 %	O'Brien & Gere 1995
The Need of a Conceptual Model Prior to Treatment	It is very important to have a model	

Summary of site conditions favorable for natural attenuation of gasoline constituents in groundwater is presented in Table 12 (Appendix B). Summary of parameters for evaluation in consideration of Natural Attenuation as a remedial strategy is presented in Tables 6, 7, and 8 (Appendix B).

FOOTNOTES - 4.50 NATURAL ATTENUATION

1. Natural attenuation is not a "technology" and is not the same as "no action," although it often is perceived as such. This approach is very suitable for low-risk sites. Natural attenuation describes monitoring and documenting the changes in concentration and distribution of contaminants over time as a result of the natural site conditions to which the contaminants are exposed in the absence of active remedial measures.

2. Relationships between soil types, particle sizes, and hydraulic conductivity are presented in Figure 1 (Appendix A).

3. The pH (hydrogen ion activity) and pE (redox potential) of the geologic materials and the waste stream strongly influence contaminant mobility. The pH affects the speciation of many dissolved chemical constituents, which in turn determines solubility and reactivity. Ion exchange and hydrolysis reactions are also particularly sensitive to pH. pE influences many precipitation and dissolution reactions, particularly those involving iron and manganese, and determines in large measure the type of biodegradation that occurs.

   Redox potential is generally expressed in volts, E, or as the negative logarithm of the electron activity, pE. At neutral pH, aerobic conditions are associated with a pE of about 13, and anaerobic by pE below -3. For each unit decrease in pH, the respective values for pE increase about one unit.

4. Cold temperatures and the depth of contamination inhibit biological degradation. If the depth of the soil that undergoes natural attenuation is deep, anaerobic conditions set in (Adriaens *et al.* 1995).

4.51 BIOFILTRATION

Engineering Parameters	Range of Values	References
Matrix Characteristics		
Moisture Content	25 % - 85%	University of Wisconsin 1995; Park and Sims 1994
pH	5- 9	McCoy and Associates 1992; USEPA 1995a
Temperature	4° C- 40° C (Optimum is 25° C)	O'Brien and Gere 1995; Norris and Eckenfelder 1994
Off-Gas Characteristics		
Type of Off-Gas Suitable[1]	Non-halogenated VOCs and fuel hydrocarbons	
Biodegradability of the Contaminants[2]	100 grams/m^3-hour	USEPA 1992g
Temperature of Off-Gas	20° C- 40° C (Optimum Range)	USEPA 1992g
Relative Humidity	95%	USEPA 1992g
Concentration of Contaminants	Typically, less than 1000 ppm. Maximum VOC 5000 mg/m^3 reported.	USEPA 1992g
Operating Parameters		
Air Flow Rate	Up to 30-120 scfm	Skladany *et al.* 1993; USEPA 1992g
Air Loading Rate[3]	2 to 10 cfm/ft^2	Prokop 1992; USEPA 1992g
Gas Contact Time	6 to 90 seconds	Skladany *et al.* 1993; O'Brien and Gere 1995
Substrate Used in the Biofilter	Porous filter such as peat, compost, wood chips, heather or other fibrous materials	Prokop 1992; Skladany *et al.* 1993
Type of Biodegradation	Aerobic	USEPA 1992g
Minimum Oxygen Content for biodegradation	5 %	O'Brien & Gere 1995
Oxygen Utilization Rates	0.02 to 0.99 percent oxygen/hour	Hinchee and Ong 1992
Temperature of the Biofilter Bed	15° C- 35 ° C	USEPA 1992g
Moisture Content of the Biofilter Bed	40 - 70%	
pH of the Filter Bed	7-8	USEPA 1992g
Typical Depth of Biofilter Material	3 - 4 feet	USEPA 1992g

4.51   BIOFILTRATION (continued)

Engineering Parameters	Range of Values	References
Can Filter Bed be Shut Down[4]	Yes. Filter beds can survive shut down periods of at least two weeks without any significant reduction in biological activity.	USEPA 1992g
Need for a Pilot Test	Usually Required	USEPA 1992g
Contaminant Removal Efficiency	99%	USEPA 1992g

FOOTNOTES - 4.51 BIOFILTRATION

1.   Halogenated VOCs can also be treated, but the process may be less effective. Biofilters have been successfully used to control odors from compost piles (USEPA 1994b).

2.   Typical biodegradable contaminants include: alcohols, ethers, aldehydes, ketones, amines, sulfides, and certain monocyclic aromatics (xylene, benzene, toluene and phenol) (USEPA 1992g).

3.   If soil bed is used in the biofilter, the air loading rate ranges from 0.1 to 0.5 cfm/ft^2 (Prokop 1992). According to USEPA (1992g), the surface loading rate is 300 m^3/hour of waste gas per m^2 of filter area.

4.   Shut down periods up to two months are feasible with nutrient addition and aeration of the filter (USEPA 1992g).

4.54 OXIDATION[1]

Engineering Parameters	Range of Values	References
Off-Gas Characteristics		
Explosive Limit of the Influent gas Concentration	< 25% of LEL	Buonicore 1992
Presence of Sulfur, Halogenated Compounds	Not Desirable	USEPA 1991h
Operating Parameters for Thermal Oxidation[2]		
Fuel Used	Propane or Natural Gas	Buonicore 1992
Heat Exchanger Efficiency (if gasoline is the contaminant)	25 - 35% and Preheat temperature is maintained below 180° C (530° F)	Buonicore 1992
Burner Capacity in the Combustion Chamber	0.5 - 2 million BTUs per hour	Buonicore 1992
Operating Temperatures[3]	760° C - 870° C (1200° F - 2000° F)	Buonicore 1992 ; USEPA 1991h
Gas Residence Time	0.2 to 2 seconds (typical is one second or less)	Buonicore 1992
Usual Length to Diameter of the Oxidizer (L:D)	2:3	Buonicore 1992
Average Gas Velocity	10 to 50 feet per second	USEPA 1991h
Refractory Wall Thickness	3 to 9 inches	Buonicore 1992
Oxygen Content	16%	USEPA 1992g
Typical Heat Recovered from Exhaust Gases	50%	Buonicore 1992
Operating Parameters for Catalytic Oxidation		
Catalysts Used[4]	Metal Oxides such as Nickel Oxide, Copper Oxide, Manganese Dioxide, or Chromium Oxide	Buonicore 1992
Shape and Size of the Catalyst	Porous pellets, usually cylindrical or spherical in shape ranging from 1/16 to 1/2 inch in diameter.	Buonicore 1992
Average Gas Velocity	10 to 30 feet per second	Buonicore 1992
Usual Length to Diameter Ratio	< 0.5	Buonicore 1992
Amount of Catalyst Needed to achieve 90 - 95% Destruction	1.5 to 2 ft[3] per 1000 cfm (of exhaust stream plus supplementary fuel combustion product)	Buonicore 1992

4.54 OXIDATION[1] (continued)

Engineering Parameters	Range of Values	References
Temperature to Preheat the Contaminants VOCs	310° C - 430° C (600° F - 800° F)	USEPA 1991h
Typical Heat Recovered from Exhaust Gases	50%	

FOOTNOTES - 4.54 OXIDATION

1. This technique employs either thermal oxidation or catalytic oxidation to destroy contaminants in the exhaust gas from air strippers and SVE systems (USEPA 1994b).

2. Thermal oxidizers can often be converted to catalytic units after initially high influent contaminant concentrations decrease to less than 1000 to 5000 ppmv.

3. According to USEPA (1994b), the temperature range is from 600° F - 700° F and according to Buonicore (1992) the range is 650° F - 800° F. Temperature range at the catalyst bed outlet is 1000° F - 1200° F. The Maximum temperature of flue gas leaving the catalyst bed is limited to 1200° F to prevent catalyst deactivation by overheating (USEPA 1991h).

4. VOCs are thermally destroyed at temperatures typically ranging from 320° C - 540° C (600° F - 1000° F) by using a solid catalyst.

4.55 VAPOR-PHASE CARBON ADSORPTION[1]

Engineering Parameters	Range of Values	References
Off-Gas Characteristics		
Type of Gas Treated	Effective for VOCs. Inorganics not desirable.	USEPA 1992f
Concentration of Contaminants	low ppb to 1000 ppm	USEPA 1992f
Molecular Weights of the Compounds that have the Proper Adsorption Properties[2]	50 - 200 grams/gram-mol	USEPA 1992f
pH	Compounds are better adsorbed at high pH (>7)	USEPA 1994b
Temperature	100 - 130° F	USEPA 1991i
Maximum Relative Humidity	50%	USEPA 1992e
Maximum Inorganics in the Vapor Phase	1000 ppm	USEPA 1992g
Operating Parameters		
Common Types of Designs[2]	1. Canister Systems with Off-site Regeneration 2. Continuous Regenerating Systems 3. Dual Bed Systems with On-site batch Regeneration	USEPA 1992g USEPA 1992h
Residence Time	0.1 second to 1 minute	
Linear Bed Velocities	8 to 200 feet per minute (8 to 100 is more common)	USEPA 1994b
Adsorption Efficiency[3]	1 gram of VOC (or hazardous air pollutant) per 10 grams of Carbon	USEPA 1992g
Handling of Spent Carbon	May be disposed of and the adsorbed contaminants may be destroyed by thermal treatment	
Maximum Allowable Flow Rate[3]	1000 scfm	USEPA 1992g
Pilot Test (Isotherm Test)	May be necessary	
Use of Regenerated Carbon	Regenerated carbon will have a lower Adsorptive Capacity	
Removal Efficiency	70 - 99%	USEPA 1992g

FOOTNOTES - 4.55 VAPOR PHASE CARBON ADSORPTION

1. Economics favor pretreatment of the VOC stream, followed by the use of a vapor-phase granular activated carbon system as a polishing step (USEPA 1994b).

2. *Carbon canisters* (a fixed-bed system) generally are used for remediation projects (USEPA 1992g). Carbon canisters are used for low vent flows, usually less than 100 cubic feet/minute and are not regenerated on-site. They are usually discarded or returned to the supplier (USEPA 1992g). *Continuous regeneration systems* are less commonly used than the fixed-bed systems (USEPA 1992g). *Dual-bed (fixed-bed)* carbon adsorbers that can be regenerated are used for controlling continuous vent streams with flows exceeding 100,000 standard cubic feet per minute (scfm) and can handle a wide range of organic concentrations (USEPA 1992h).

3. Carbon has a fixed capacity of number of active adsorption sites. If adsorption were continued beyond this point, then the "break through" point would be reached, and pollutants would no longer be controlled effectively. Eventually, "saturation" would be reached, where all sites are filled and virtually no adsorption occurs (USEPA 1992g).

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APPENDIX A

REMEDIATION MATRIX AND PROCESS EVALUATION DATA

Figure 1. Relationship Between Particle Size, Hydraulic Conductivity (K) and Permeability (k)

(USEPA 1991j; Freeze and Cheny 1979)
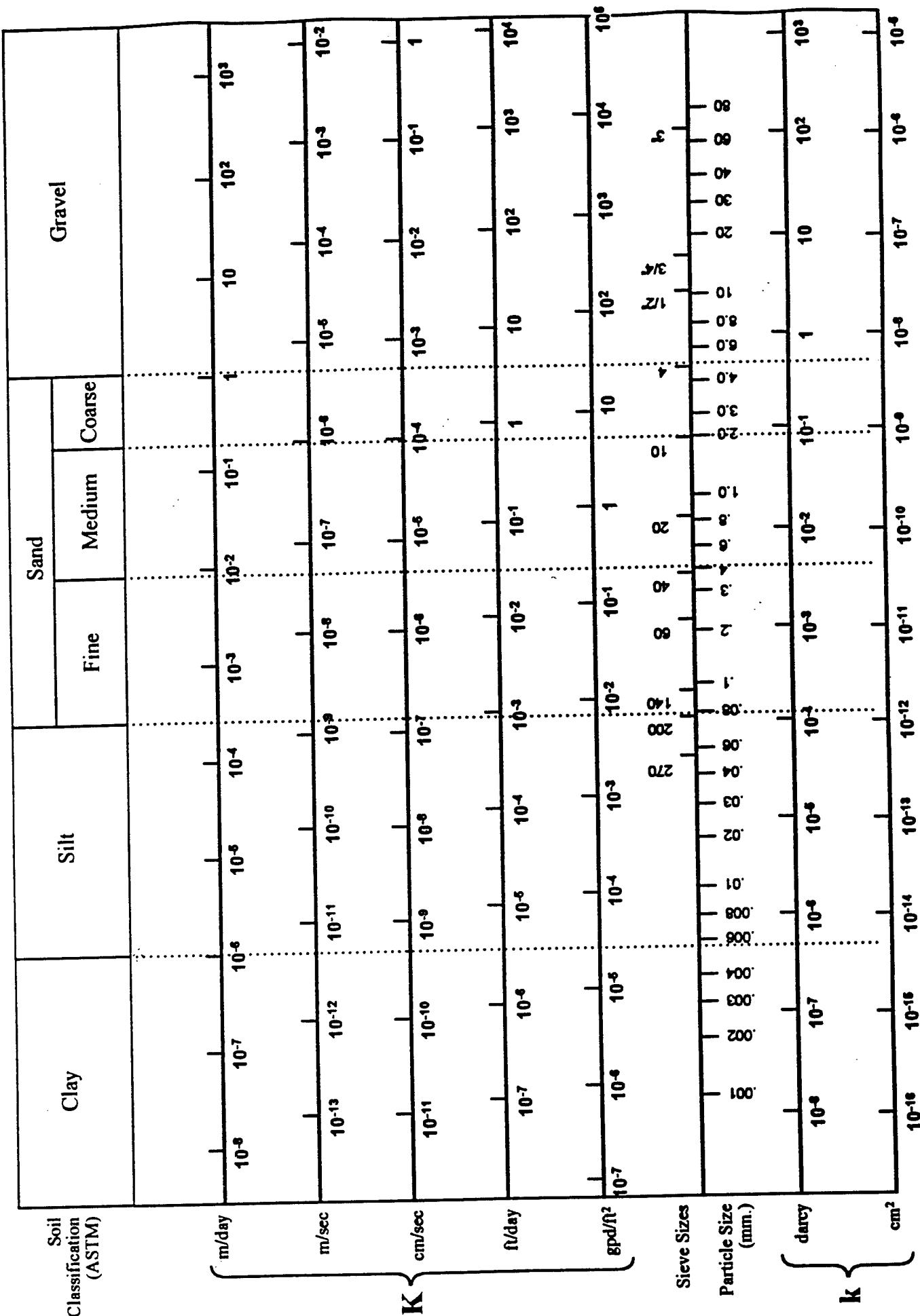
Figure 2

Impact of physicochemical properties on potential for bioventing.
(USEPA 1993a)

H = Henry's Law Coefficient (atm•m^3•mole^{-1})

Vapor Pressure Too High to Biovent

Vapor Pressure Amenable to Bioventing or Volatilization

Vapor Pressure Too Low to Volatilize

Vapor Pressure (atm)
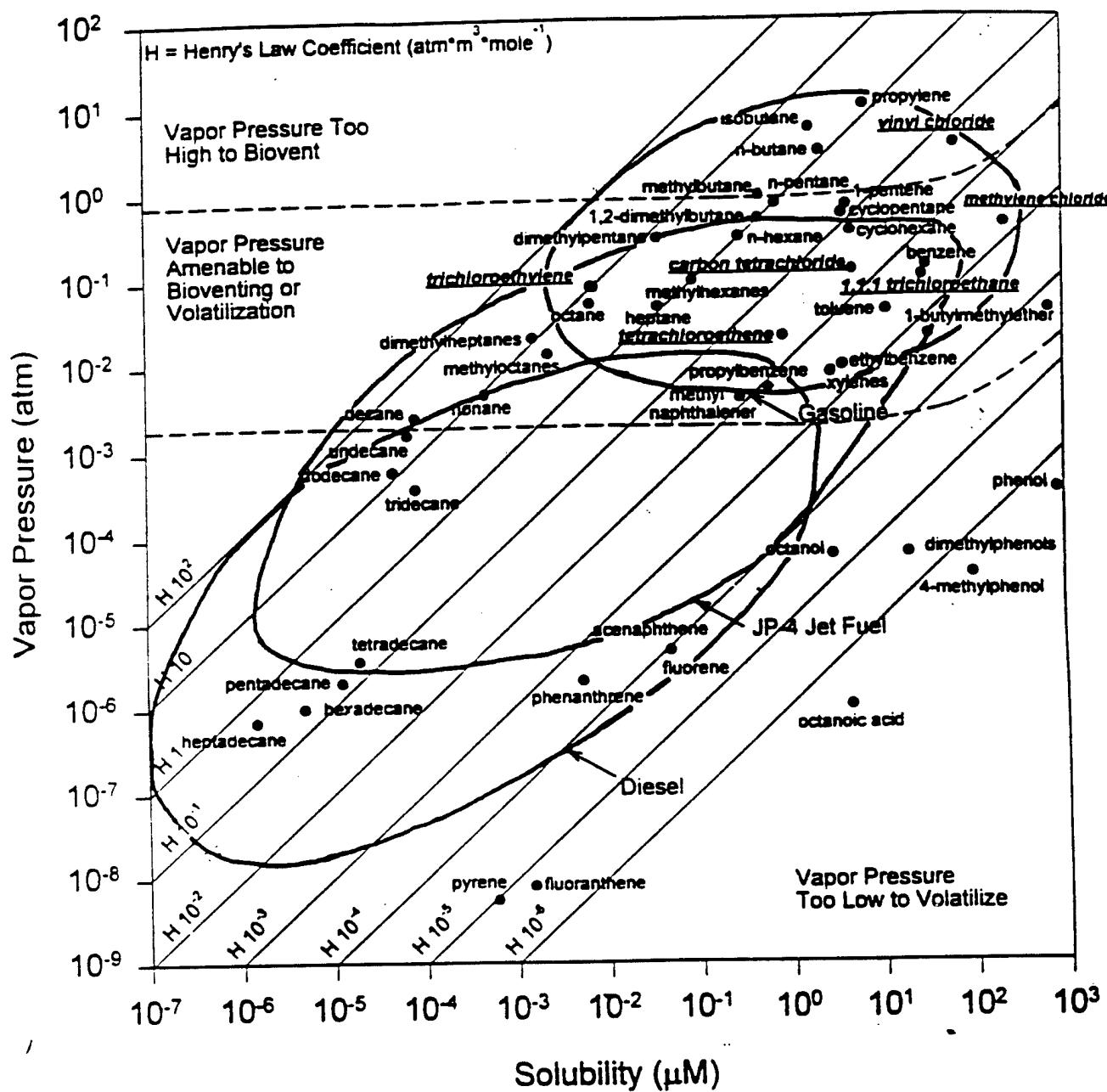
Solubility (μM)

Bold Underline - chemicals commonly found at USCG facilities

(See Table 10 in Appendix B, Solubility for Specific Organic Compounds)

A-3

FIGURE 3
Decision Flow Diagram for Groundwater Contamination
(Source: USEPA 1990c)
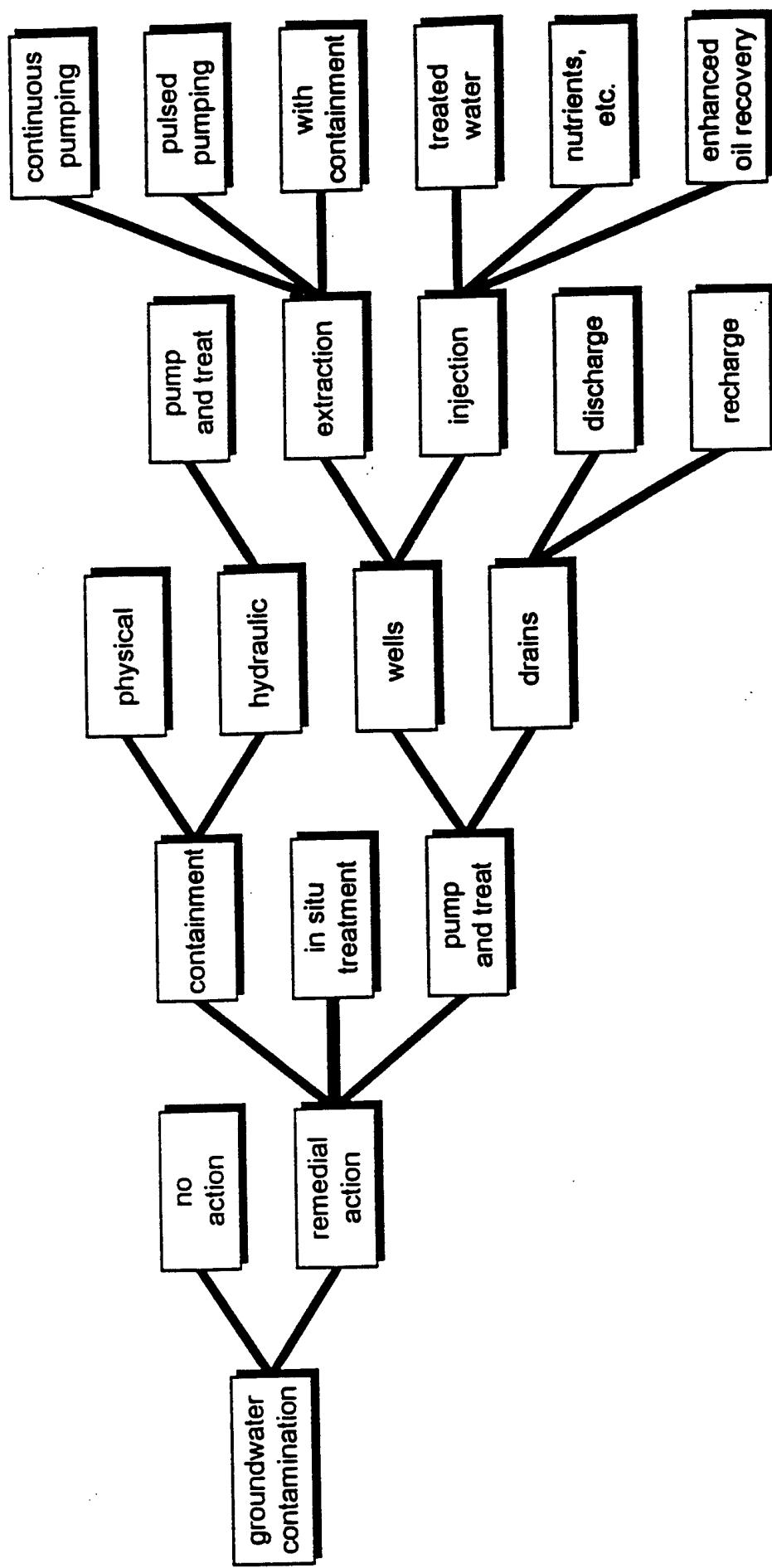
APPENDIX B

CHEMICAL & REMEDIATION PROCESS DATA

TABLE 1: Classes of Chemicals that May Be Suitable for Bioremediation
(USEPA 1991a)

Class	Example	Using Aerobic Biodegradation Process	Using Anaerobic Biodegradation Process
Monochlorinated aromatic compounds	Chlorobenzene	●	
Benzene, toluene, xylene		●	●
Nonhalogenated phenolics and cresols	2-methyl phenol	●	●
Polynuclear aromatic hydrocarbons	Creosote	●	
Alkanes and alkenes	Fuel oil	●	
Polychlorinated biphenyls	Trichlorobiphenyl	●	●
Chlorophenols	Pentachlorophenol	●	●
Nitrogen heterocyclics	Pyridine	●	
Chlorinated solvents Alkanes Alkenes	Chloroform Trichloroethylene	● ●	● ●

TABLE 2: Trace Nutrient Requirements for Biological Oxidation
(Norris and Eckenfelder 1994)

Nutrients		mg/mg Biochemical Oxygen Demand (BOD)
Mn	===>	10×10^{-5}
Cu	===>	15×10^{-5}
Zn	===>	16×10^{-5}
Mo	===>	43×10^{-5}
Se	===>	14×10^{-10}
Mg	===>	30×10^{-4}
Co	===>	13×10^{-5}
Ca	===>	62×10^{-4}
Na	===>	5×10^{-5}
K	===>	45×10^{-4}
Fe	===>	12×10^{-3}
CO_3	===>	27×10^{-4}

TABLE 3: Henry's Law Constant for Specific Organic Compounds (Nyer 1993)

Compound	Henry's Law Constant[a] (atm)
Acenaphthene	5.1
Acetone	0
Aroclor 1254	150
Benzene	230
Benzo(a)pyrene	0.1
Benzo(g,h,i)perylene	0
Benzoic Acid	0
Bromodichloromethane	127
Bromoform	35
Carbon Tetrachloride	1,282
Chlorobenzene	145
Chloroethane	34
Chloroform	171
2-Chlorophenol	0.93
p-Dichlorobenzene (1,4)	104
1,1-Dichloroethane	240
1,2-Dichloroethane	51
1,1 Dichloroethylene	1,841
cis-1,2-Dichloroethylene	160
trans-1,2,-Dichloroethylene	429
2,4-Dichlorophenoxyacetic Acid	10
Dimethyl Phthalate	0
2,6-Dinitrotoluene	0.2
1,4-Dioxane	0.6
Ethylbenzene	359
bis(2-Ethylhexyl)phthalate	0
Heptachlor	46
Hexachlorobenzene	37.8
Hexachloroethane	138
2-Hexanone	1.6
Isophorone	0.3
Methylene Chloride	89
Methyl Ethyl Ketone	1.16
Methyl Naphthalene	3.2
Methyl tert-Butyl Ether	196

TABLE 3: Henry's Law Constant for Specific Organic Compounds (Nyer 1993) (continued)

Compound	Henry's Law Constant[a] (atm)
Naphthalene	20
Nitrobenzene	1.2
Pentachlorophenol	0.15
Phenol	0.017
1,1,2,2-Tetrachloroethane	21
Tetrachloroethylene	1,035
Tetrahydrofuran	2
Toluene	217
1,2,4-Trichlorobenzene	128
1,1,1-Trichloroethane	390
1,1,2-Trichloroethane	41
Trichloroethylene	544
2,4,6-Trichlorophenol	0.2
Vinyl Chloride	355,000
o-Xylene	266

[a] at water temperature of 68°F

TABLE 4: Solidification/Stabilization (USEPA 1993b)

Binder Material Used	Binder/Soil Ratio (Calculated on a Dry Weight Basis)
Portland Cement (100%)	45 %
Kiln Dust and Fly Ash (2:1)	139.5%
Fly Ash and Quicklime (3:2)	77.5%
Portland Cement (100%) (soil heated prior to treatment to remove organic carbon)	20%

TABLE 5: Solvent Extraction – Redox Processes (USEPA 1995i)

	Solvents	Pilot Plant Capacity	Full Scale Plant Capacity	Particle Size	Temp.	Electrical Requirements	Other Parameters	Notes
BEST Process	Triethylamine (TEA)	100 lb/day	100 ton/day	<2.5 cm	(TEA) heated to 55-80 °C		pH 10.5-11	Mixing time 5-15 min.; full scale plant only treats pumpable waste; TEA highly flammable, requires 100 ft radius control zone, causes severe odor problems
CF Systems	Liquid CO_2 for aqueous solution, propane or propane/ butane mixture for sediments and sludges		25 ton/day	<19 mm	15 - 50 °C	All electrical equipment must be explosion proof	pH 6-10 Viscosity <5,000 centipoise	Extraction efficiencies 80-100 %; extraction stages 2-5; OSHA Level B PPE needed for personnel handling wastes

TABLE 5: Solvent Extraction – Redox Processes (USEPA 1995i) (continued)

	Solvents	Pilot Plant Capacity	Full Scale Plant Capacity	Particle Size	Temp.	Electrical Requirements	Other Parameters	Notes
Carver-Greenfield Process		100 lb/hr	0.33 to 420 dry ton/day	<6 mm	43-177 °C	Requires 480V, three phase power; consumption 1.7 billion joule/tonne	Operating pressure 10.3 to 103.5 kPa	1620 scfm/hr nitrogen consumption for wastes consisting of 52% solids, 17% indigenous oil, 31% water
Extraksol Process			1-10 ton/hr	nonporous <0.6m; porous ≤5.1 cm			Moisture content <30%; clay content <40%	Emission control - activated carbon for vented process gases
Low-Energy Extraction Process	Hydrophilic leaching solvent; PCB uses acetone, coal tars use acetone & proprietary solvent			<203 mm (full scale); <6 mm (pilot scale)			Moisture content; 50%	Solvents recycled; wastewater treated by carbon adsorption

TABLE 5: Solvent Extraction - Redox Processes (USEPA 1995i) (continued)

	Solvents	Pilot Plant Capacity	Full Scale Plant Capacity	Particle Size	Temp.	Electrical Requirements	Other Parameters	Notes
Nu KEM Process				<5cm (2 in)			extraction stages 3 - 5; solvent to soil ratio 1:1 to 2:1 by weight; moisture <10%	
Soil Restoration Unit				$\leq$7.6 cm (3 in.)			capacity; mobile unit 2 ton/hr; full scale 3,000 tons; moisture <20%	solvents are flammable

TABLE 6: Summary of Parameters for Evaluation In Consideration of Natural Attenuation As a Remedial Strategy (Testa 1995)

Parameter Group	Parameter for Evaluation
Hydrogeologic	Gradient
	Permeability
	Recharge
	Moisture Content/Field Capacity
	Depth to Contaminant
	Dissolved Oxygen
	Soil Gas
	Extent of Contamination/Plume Stability
Chemical	Hydrocarbon Type
	Chromatographic Evidence
	Hydrocarbon Concentration
	Soil pH
	Redox Potential
	Nitrogen, Phosphorous and other nutrients
Biological	Microscopic Examination
	Plate Counts
	Total Heterotrophs
	Petroleum Degraders
	Total Organic Carbon
Circumstantial	Time Required for Cleanup
	Age of Release

**TABLE 7: Summary of Site Conditions Favorable for Natural Attenuation
of Diesel Range Hydrocarbons in Soil (Testa 1995)**

Parameter for Evaluation	Site Specific Conditions
Soil Permeability	Unconsolidated outwash gravels and sand; K=2 cm/sec.
Recharge	+1100mm annual rainfall; annual water table fluctuations typically 600-900mm.
Depth to Groundwater	2.5-3.5 meters.
Soil Moisture Content	Upper smear zone - 18% of field capacity.
Soil pH	Neutral - 6.8
Soil Gas $O_2 CO_2$	Not measured.
Hydrocarbon Type	Jet fuel and light diesel mixture.
Hydrocarbon Concentration	Average for Upper Smear Zone - 1,000 mg/kg TPH (a). Average for Lower Smear Zone - 10,000 mg/kg TPH.
Total Heterotrophs	Upper Smear Zone - 106 CFU/g/soil. Lower Smear Zone - 105 CFU/g soil. Background - 102 CFU g soil.
Total Hydrocarbons	Upper Smear Zone - 105 CFU/g soil. Lower Smear Zone - 105 CFU/g soil. Background - 102 CFU g soil.
Degraders (b) Microscopic Examination of Bacteria	Upper Smear Zone - Bacteria intact, healthy. Lower Smear Zone - Bacteria, grainy, unhealthy appearance, many protozoans appearance, no protozoans.
Chromatographic Interpretation	Loss of volatiles and degradation of n-alkanes in the upper smear zone soil; Lower smear zone relatively less degraded.
% Volatiles (c)	Upper Smear Zone - 10%. Lower Smear Zone - 25%.
(a) TPH measured as sum of total volatile and total extractable hydrocarbons. (b) Determined using Sheen Screen. (c) % Volatiles defined as (total volatile hydrocarbons/total extractable hydrocarbons) x 100.	

TABLE 8: Factors to be Considered for Natural Attenuation (USEPA 1993a)

Serial Number	Factors to be Considered
1	SITE CHARACTERIZATION FOR NATURAL ATTENUATION • Detailed description of the subsurface hydrology and geology • Delineation of the contaminant source area and any mobile NAPLs • Delineation of the horizontal and vertical extent of the contaminant plume • Identification of any downgradient receptors (wells or surface discharges) that could potentially be affected
2	SPECIFIC QUESTIONS THAT SHOULD BE ADDRESSED FOR NATURAL ATTENUATION • Is the contaminant biodegradable? • Is biodegradation occurring in the aquifer? • Are environmental conditions appropriate for biodegradation? • If the waste does not completely biodegrade, where will it go?
3	CONTAMINANT PLUME PARAMETERS TO BE MONITORED • Individual contaminant components • Dissolved oxygen • Nitrate • Dissolved iron • Redox potential • Carbon dioxide • pH • Total organic carbon
4	TWO OF THE MOST COMMONLY USED MODELS FOR SIMULATING HYDROCARBON BIODEGRADATION ARE: • First order decay models • BIOFLUME II

TABLE 9: Vapor Extractability of Selected Volatile Organic Compounds (Angell 1992)

Compound	Vapor Pressure @ 40°F (mm Hg)	Maximum-Vapor Extractability[1]	
		lb/100 ft³	lb/day @ 100 scfm
Benzene	28.0	7.9	1134.0
Toluene	9.0	3.0	430.0
Xylenes	3.0	1.1	165.0
Methylene Chloride	198.9	59.9	8622.0
Chloroform	77.0	33.2	4782.0
1,1 DCA	89.0	31.7	4564.0
1,1,1 TCA	4.6	21.9	3154.0
TCE	28.0	13.1	1891.0
PERC	7.5	4.49	646.0
Chlorobenzene	3.8	1.5	221.0
Naphthalene	0.1	0.05	7.0

[1]Assumes continuous vapor saturation

TABLE 10: Solubility for Specific Organic Compounds (Nyer 1993)

Compound	Solubility[a] (mg/L)
Acenaphthene	3.42
Acetone	1×10^{6a}
Aroclor 1254	1.2×10^{-2}
Benzene	1.75×10^3
Benzo(a)pyrene	1.2×10^{-3}
Benzo(g,h,i)perylene	7×10^{-4}
Benzoic Acid	2.7×10^3
Bromodichloromethane	4.4×10^3
Bromoform	3.01×10^3
Carbon Tetrachloride	7.57×10^2
Chlorobenzene	4.66×10^2
Chloroethane	5.74×10^3
Chloroform	8.2×10^3
2-Chlorophenol	2.9×10^4
p-Dichlorobenzene (1,4)	7.9×10^1
1,1-Dichloroethane	5.5×10^3
1,2-Dichloroethane	8.52×10^3
1,1 Dichloroethylene	2.25×10^3
cis-1,2-Dichloroethylene	3.5×10^3
trans-1,2,-Dichloroethylene	6.3×10^3
2,4-Dichlorophenoxyacetic Acid	6.2×10^2
Dimethyl Phthalate	4.32×10^3
2,6-Dinitrotoluene	1.32×10^3
1,4-Dioxane	4.31×10^5
Ethylbenzene	1.52×10^2
bis(2-Ethylhexyl)phthalate	2.85×10^{-1}
Heptachlor	1.8×10^{-1}
Hexachlorobenzene	6×10^{-3}
Hexachloroethane	5×10^1
2-Hexanone	1.4×10^4
Isophorone	1.2×10^4
Methylene Chloride	2×10^4

[a] Solubility of 1,000,000 mg/L assigned because of reported "infinite solubility" in the literature.

TABLE 10: Solubility for Specific Organic Compounds (Nyer 1993)
(continued)

Compound	Solubility[a] (mg/l)
Methyl Ethyl Ketone	2.68×10^5
Methyl Naphthalene	2.54×10^1
Methyl tert-Butyl Ether	4.8×10^4
Naphthalene	3.2×10^1
Nitrobenzene	1.9×10^3
Pentachlorophenol	1.4×10^1
Phenol	9.3×10^4
1,1,2,2-Tetrachloroethane	2.9×10^3
Tetrachloroethylene	1.5×10^2
Tetrahydrofuran	3×10^5
Toluene	5.35×10^2
1,2,4-Trichlorobenzene	3×10^1
1,1,1-Trichloroethane	1.5×10^3
1,1,2-Trichloroethane	4.5×10^3
Trichloroethylene	1.1×10^3
2,4,6-Trichlorophenol	8×10^2
Vinyl Chloride	2.67×10^3
o-Xylene	1.75×10^2

[a] Solubility of 1,000,000 mg/L assigned because of reported "infinite solubility" in the literature.

TABLE 11: Adsorption Capacity for Specific Organic Compounds (Nyer 1993)

Compound	Adsorption Capacity (mg/g)
Acenaphthene	155
Acetone	43
Aroclor 1254	NA
Benzene	80
Benzo(a)pyrene	24.8
Benzo(g,h,i)perylene	8.3
Benzoic Acid	40 (at pH = 3)
Bromodichloromethane	5
Bromoform	13.6
Carbon Tetrachloride	6.2
Chlorobenzene	45
Chloroethane	0.3
Chloroform	1.6
2-Chlorophenol	38
p-Dichlorobenzene (1,4)	87.3
1,1-Dichloroethane	1.2
1,2-Dichloroethane	2
1,1 Dichloroethylene	3.4
cis-1,2-Dichloroethylene	9
trans-1,2,-Dichloroethylene	2.2
2,4-Dichlorophenoxyacetic Acid	NA
Dimethyl Phthalate	91.2
2,6-Dinitrotoluene	116
1,4-Dioxane	0.5 - 1.0
Ethylbenzene	18
bis(2-Ethylhexyl)phthalate	3995
Heptachlor	631.5
Hexachlorobenzene	42
Hexachloroethane	74.2
2-Hexanone	<13
Isophorone	24.4
Methylene Chloride	0.8

NA = Not Available

TABLE 11: Adsorption Capacity for Specific Organic Compounds (Nyer 1993)
(continued)

Compound	Adsorption Capacity (mg/g)
Methyl Ethyl Ketone	94
Methyl Naphthalene	150
Methyl tert-Butyl Ether	6.5
Naphthalene	5.6
Nitrobenzene	50.5
Pentachlorophenol	100
Phenol	161
1,1,2,2-Tetrachloroethane	8.2
Tetrachloroethylene	34.5
Tetrahydrofuran	<0.5
Toluene	50
1,2,4-Trichlorobenzene	126.6
1,1,1-Trichloroethane	2
1,1,2-Trichloroethane	3.7
Trichloroethylene	18.2
2,4,6-Trichlorophenol	179 (at pH = 3)
Vinyl Chloride	TRACE
o-Xylene	75

NA = Not Available

TABLE 12: Summary of Site Conditions Favorable for Natural Attenuation of Gasoline Constituents in Groundwater (Testa 1995)

Parameter for Evaluation	Site Specific Conditions
Source Recovery	Former USTs and hydrocarbon-affected soil have been removed.
Depth of Groundwater	Shallow at 3.5-4.5 meters.
Gradient	Seasonally consistent.
Extent of Contamination/Plume Stability	Extent of plume reduced via pump and treat plume is stable; asymptotic conditions reached.
Dissolved Oxygen	Aerobic biodegradation occurring as evidenced by inverse relationship between dissolved BTEX and DO.
Continued Groundwater Monitoring	Adequate groundwater monitoring system in place.
Water-Bearing Zone Imported	Non-beneficial use of groundwater.